Development of a Procedure for the Selection of Candidate Vessels of Opportunity in Support of the Submarine Rescue Diving and Recompression System

by

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B.S. Mechanical Engineering
United States Naval Academy, 1999

Submitted to the Department of Ocean Engineering in Partial Fulfillment of Requirements for the Degrees of

Naval Engineer

and

Master of Science in Ocean Systems Management

at the
Massachusetts Institute of Technology
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ABSTRACT

The U.S. Navy's new system for rescuing stranded submariners, the Submarine Rescue Diving and Recompression System (SRDRS), utilizes a tethered, remotely operated Pressurized Rescue Module (PRM) deployed and controlled from a Vessel of Opportunity (VOO). The PRM is capable of docking with the disabled submarine at pressure and rescuing up to 16 personnel per sortie. The PRM is launched and recovered using a deck mounted A-frame crane called the Launch and Recovery System (LARS). Upon recovery, the PRM docks with the Submarine Decompression System (SDS) to allow transfer and decompression of personnel. The PRM, LARS, SDS, and associated generators and auxiliaries all compose the Submarine Rescue System (SRS). The SRS, approximately 183 tons, is installed aboard the VOO.

The SRS was nominally designed for operation on the U.S. Navy's Auxiliary Fleet Tug, T-ATF, but is actually intended to be a fly-away system, capable of being installed on any available VOO near the disabled submarine. The VOO may be any Offshore Supply Vessel (OSV), Anchor Handling Tug, or offshore barge that has the capacity to handle the SRS and is available in the area of a disabled submarine. Since the SRS must be rapidly deployed, potential VOOs must be quickly identified and evaluated for structural, stability and seakeeping suitability with respect to the requirements for the SRS.

This thesis describes the theoretical background and development of a procedure intended to aid in the analysis and evaluation of potential VOOs for stability and seakeeping suitability. This procedure utilizes limited information about the potential VOO such as length, beam, draft, depth, deck strength, dead weight tonnage, etc. as inputs for rapidly modeling hull geometry. The developed hull geometry is combined with an empirically derived weight distribution which serve as the input for stability analysis for several different load cases and the seakeeping analysis. Theoretical and empirical analyses are used to justify the requisite assumptions and estimates used in developing the VOO stability and seakeeping models. The efficacy of this VOO evaluation process is demonstrated by both a comparison to known stability and seakeeping analyses for the T-ATF, and with a sensitivity analysis of assumed variables.

With this process, the U.S. Navy will be able to rapidly analyze and evaluate the stability and seakeeping characteristics of potential Vessels of Opportunity and judge their suitability to carry and deploy the Submarine Rescue System.

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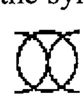
ACRONYMS

AHT	Anchor Handling Tug
AP	After Perpendicular
ASRV	Australian Submarine Rescue Vehicle
ASSET	Advanced Surface Ship Evaluation Tool
AUWS	Advanced Underwater Work System
B	Beam
BL	Baseline
CL	Center Line
COTS	Commercial Off The Shelf
D	Depth
DISSUB	DISabled SUBmarine
DSRV	Deep Submergence Rescue Vehicle
DTL	Deck Transfer Lock
DWT	Dead Weight Tonnage
FP	Forward Perpendicular
IMO	International Maritime Organization
ISO	International Organization for Standardization
LARS	Launch And Recovery System
LBP	Length Between Perpendiculars
LOA	Length Over-All
LWL	Length on Water Line
MOSUB	Mother Submarine
MOSHIP	Mother Ship
MS	Midships, also indicated by the symbol: 
NAVSEA	Naval Sea Systems Command
NSRS	NATO Submarine Rescue System

OPL	Oilfield Publications, Ltd.
OSV	Offshore Supply Vessel
POSSE	Program of Ship Salvage and Engineering
PRM	Pressurized Rescue Module
RAO	Response Amplitude Operator
ROV	Remotely Operated Vehicle
SDS	Submarine Decompression System
SMP	Ship Motions Program
SRC	Submarine Rescue Chamber
SRDRS	Submarine Rescue Diving and Recompression System
SRS	Submarine Rescue System
T	Draft
TUP	Transfer Under Pressure
VAA	VOO Adequacy Analysis Procedure
VOO	Vessel Of Opportunity
WL	Water Line
USCG	United States Coast Guard

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Chapter 1. INTRODUCTION

1.1. Submarine Rescue Diving and Recompression System

The Submarine Rescue Diving and Recompression System (SRDRS) is a transportable, modular submarine rescue system that will be capable of rapid deployment anywhere in the world for operations from a Vessel Of Opportunity (VOO) instead of a dedicated mother-ship. The SRDRS consists of two separate systems, shown in Figure 1.1 and Figure 1.2: the Advanced Underwater Work System (AUWS), and the Submarine Rescue System (SRS). The SRS is further divided into the Pressurized Rescue Module (PRM) and its associated support equipment, and the Submarine Decompression System (SDS).

Figure 1.1. AUWS (NAVSEA 2004, 7)

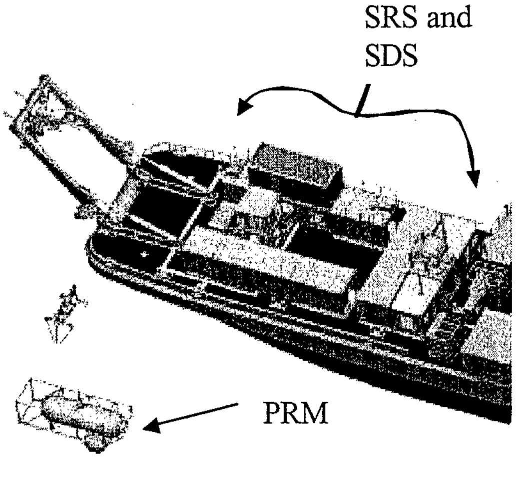

Figure 1.2. SDS, SRS and PRM (NAVSEA 2004, 36)

All SRDRS systems are packaged with standard ISO (International Organization for Standardization) container corner interfaces and with weight and size to allow for transport on

standard 40 ft trailer chassis. All this enables the SRDRS components to be transported with commercial carriers.

Upon receiving notice of a Disabled Submarine (DISSUB), the SRDRS components will depart from their storage warehouse in San Diego, California, travel by truck and airplane to the airport nearest the location of the selected VOO. The SRDRS will then be trucked to the seaport where the VOO is located. The AUWS will depart on its own dedicated VOO and transit to the location of the disabled submarine. Once on scene, the AUWS will assess the general situation, prepare the area and clear the submarine's hatch. After the SRS is installed on its VOO, it will transit to the location of the disabled submarine and begin rescue operations. The PRM (Figure 1.3) is a Remotely Operated Vessel (ROV) controlled from a console on the VOO and deployed using the Launch and Recovery (LARS) A-frame.

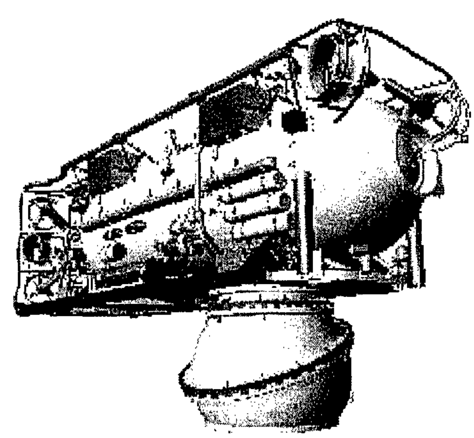

Figure 1.3. Pressurized Rescue Module (NAVSEA 2004, 72)

After launch, the PRM is driven down to the disabled submarine where the PRM's transfer skirt attaches under pressure to the submarine's hatch. Two attendants onboard the PRM then aid in transferring disabled submarine crew members to the PRM. Once the PRM is full (16

submariners and 2 attendants) and the disabled submarine's hatch is secured, the PRM returns to the VOO. The PRM is recovered via the LARS and attached to the Deck Transfer Lock (DTL) (Figure 1.4). The DTL is directly attached to the SDS, enabling the transfer of the rescued submariners at pressure.

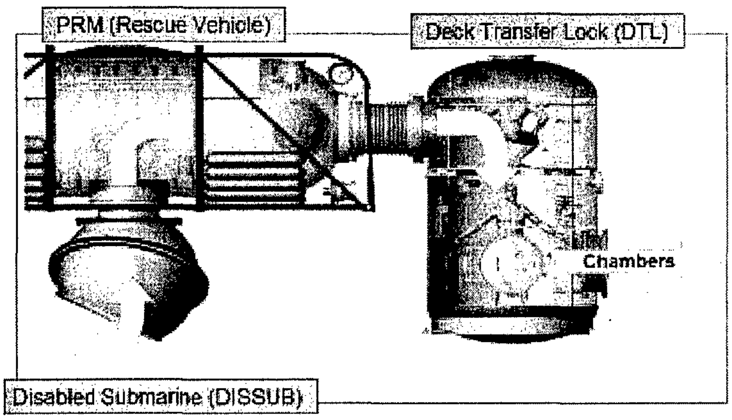

Figure 1.4. Transfer of Personnel to the SDS (NAVSEA 2004, 64)

The SDS consists of two hyperbaric chambers which can decompress 31 people in each for a total of 155 people over multiple PRM sorties. Once in the SDS, submariners are decompressed and treated for other casualties they may have.

The rapid deployment scheme of the SRDRS requires every event in the sequence of moving the system from its warehouse to the site of the disabled submarine be planned in advance, before any submarine disaster occurs. Since transportation modes are standardized, loading for trucks and airlift can be readily planned. VOO selection, on the other hand, is the one element in this chain that escapes easy planning. Although the VOO could potentially be any kind of Offshore Supply Vessel (OSV), Anchor Handling Tug (AHT), offshore barge, or similar vessel, the sheer number of different vessels which could potentially be used precludes making any kind of generalizations on ship type that might reflect adequacy for a vessel to be a VOO. Instead, the contractor coordinating the SRDRS deployment may only know limited information about the vessels which are in the area of a disabled submarine. Selection of the

VOO must be based on that limited knowledge, which is most likely only basic characteristics such as length, beam, draft, Dead Weight Tonnage (DWT), etc.

1.2. History and Background of Submarine Rescue

One person more than any other is responsible for the establishment and development of submarine rescue: Vice Admiral Charles "Swede" Momsen, USN. On September 25, 1925, Lieutenant Commander Momsen had command of his first submarine, the S-1, and was dispatched to aid in the search for the submarine S-51 which had been lost after being struck by a merchant ship. Momsen located an oil slick marking the general area where S-51 was lost but was unable to pinpoint the sub or effect any sort of rescue (ONR n.d.). When S-51 was recovered, Lieutenant Commander Momsen discovered that three (one of whom was a close friend of Momsen's) of the 36 officers and crew of S-51 had survived the collision only to die during their hopeless struggle to escape (USS Momsen n.d.). Shortly after the S-51 accident, the S-4 sank off Cape Cod. This time six submariners survived for three days in the torpedo room (ONR n.d.). The S-4 incident further reinforced Momsen's resolve to take corrective actions as he later described in a 1939 lecture to the Harvard Engineering Society:

> *Eleven years ago [1928] the first diving bells for rescuing men from submarines were designed by the Bureau of Construction and Repair, Navy Department. A curious quirk of circumstances led up to this incident. While in command of the submarine S-1 [SS-105], in 1926, I wrote to the Bureau of Construction and Repair and recommended the adoption of a diving bell for the purposes of rescuing entrapped personnel from submarines. The S-1 carried the only submarine airplane hanger in the Navy and I completed tests with a new type of plane during my tours of duty. This hanger was a tank 20 feet long and 6 feet in diameter. When I was relieved of command of the S-1, I went to the Navy Department, Bureau of Construction and Repair, for duty in the Submarine section. There I found my letter about the diving bell, unanswered. A short time later I handled a letter from the new commanding officer of the S-1, stating that the airplane tank was of no further use, requesting authority to remove it, and requesting disposition. I felt opportunity knocking and prepared a reply to send it to New York there to be cut in half and used to make two diving bells for experimental purposes. (Momsen 1939)*

Momsen's efforts in developing the rescue chamber and the "Momsen Lung" submarine rescue breathing device, first at the Bureau of Ships and then at the Submarine Safety Test Unit

and Experimental Dive Unit, formed the genesis of the Navy's submarine rescue capability. The initial rescue chamber design developed by Momsen was further refined by his relief at the Experimental Diving Unit, Commander Allan McCann (both shown with the Secretary of the Navy in Figure 1.5).

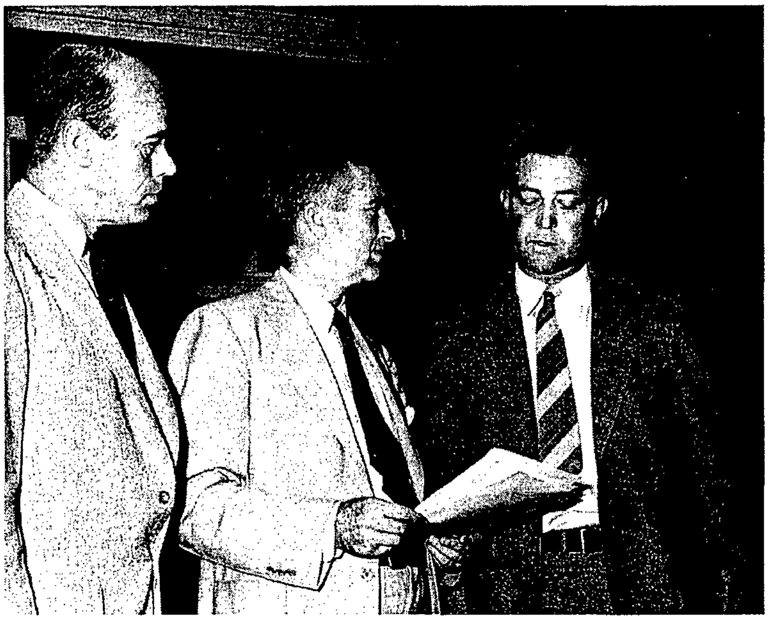

Figure 1.5. ***left*** **Cdr. McCann,** ***center*** **Secretary of the Navy Edison,** ***right*** **Cdr. Momsen (US Navy 1939)**

The final rescue chamber design (Figure 1.6 and Figure 1.7) was finished in 1930 and dubbed the "McCann Rescue Chamber." It consisted of a two chamber diving bell with ballast tanks and a rubber skirt that would aid in creating a seal when the chamber mates with the escape hatch of a disabled submarine. The upper chamber housed two operators and up to seven rescued submariners. The lower chamber would be isolated from the upper chamber while mating to the escape hatch in high pressure.

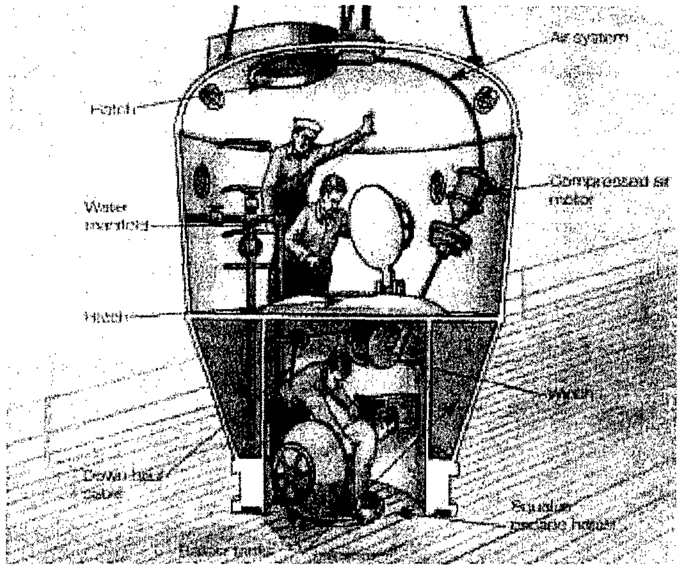

Figure 1.6. McCann Rescue Chamber Interior View (Dunmore 2002, 81)

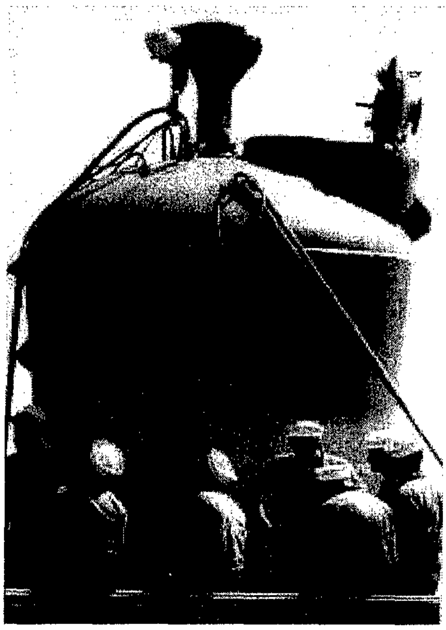

Figure 1.7. McCann Rescue Chamber Initial Testing (Dunmore 2002, 80)

As shown in Figure 1.8, The McCann Rescue Chamber was deployed from an auxiliary ship using winches and cranes controlling a cable attached to the top of the chamber. When conducting submarine rescue operations, a diver would first have to locate the escape hatch and

attach a downhaul wire. The wire would then serve to guide the rescue chamber directly to the escape hatch. After being hoisted into the water, the rescue chamber would fill its ballast tanks and dive to the escape hatch, traveling along the guide wire. Once the rescue chamber was in place and bolted to the escape hatch, the lower chamber air pressure would be reduced to create a tight seal and facilitate the transfer of personnel.

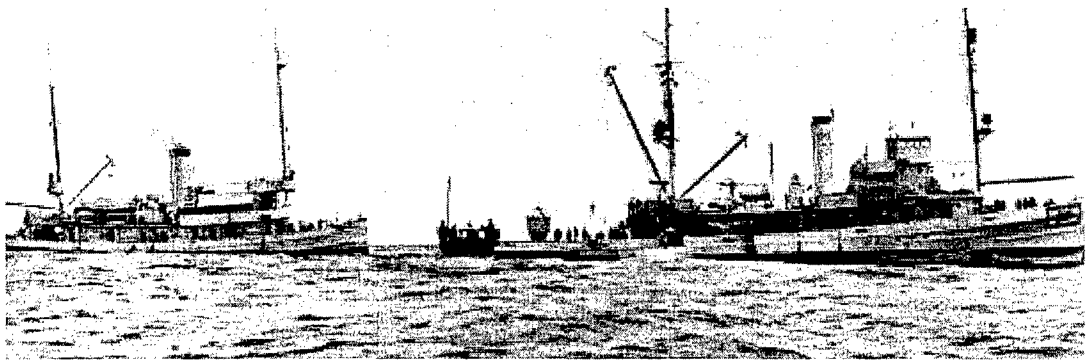

Figure 1.8. McCann Rescue Chamber At-Sea Testing (Dunmore 2002, 80)

Momsen's (and McCann's) tenacity in establishing submarine rescue capability was soon to pay off. On May 23, 1939, the USS Squalus (SS 192) departed its homeport of Portsmouth, New Hampshire, on acceptance trials. While on its nineteenth test dive, flooding in the after engine room was reported. The diving officer immediately blew forward and emergency ballast tanks. Squalus momentarily leveled but then rapidly sank by the stern coming to rest on the seafloor, 243 feet below the surface. Contrary to indicator lights, a main induction valve for diesel engine air had somehow opened causing the rapid flooding of the aft compartments and immediate drowning of 26 men in those compartments. In the forward compartments, where air pressure had rapidly increased due to the flooding, commanding officer Lieutenant Oliver F. Naquin ordered the distribution of Momsen Lungs but decided to delay escape and wait for rescue since their depth was beyond what was deemed safe. (Dunmore 2002, 74-84; Maas 1999; US Navy 1939; US Navy 2000;)

Five hours after the Squalus sank, its sister ship, USS Sculpin began searching at the Squalus' reported position prior to diving. Due to an error ashore in recording that position, Sculpin was searching five miles from Squalus' actual position. Finally, Ensign Ned Denby on

the bridge of Sculpin spotted flares from Squalus. Sculpin arrived on scene and was able to momentarily establish sound-powered phone contact with Squalus before a large wave caused the line to snap. Squalus sat on the bottom, with 33 men in cold dark silence. (Dunmore 2002, 77)

Twenty-three hours after Squalus went down, USS Falcon arrived on scene carrying the McCann rescue chamber. Also arriving was Lieutenant Commander Momsen, sent to supervise the rescue. Divers quickly found Squalus and attached the downhaul wire to the escape hatch. Momsen decided it was too dangerous to risk five sorties that would be required if each trip was limited to rescuing seven people. Instead, the first sortie returned seven people, the second and third nine people (Figure 1.9).

Figure 1.9. Squalus Rescue in Progress (Dunmore 2002, 82)

The fourth and final sortie brought the remaining eight submariners aboard the rescue chamber, including Lieutenant Naquin. As the chamber ascended, the sheave hauling in the chamber's wire rope jammed and the wire rope began to part. In order to prevent the loss of the chamber, it was lowered to the sea floor. Divers were sent down to attach a second hoist cable. After two attempts failed with the divers succumbing to the extreme depth (and being brought back to the surface for decompression treatment), Momsen decided to recover without cables – using only ballast control. After four and a half hours on the bottom, the rescue chamber rose towards the

surface; guided by what remained of the wire rope being hauled in manually by ten men. (Momsen 1939; Dunmore 2002, 83)

Although 26 men perished on Squalus, 33 men were saved. Momsen remained on the scene of the disaster to supervise the salvage and recovery of Squalus. With the arrival of the McCann rescue chamber, the U.S. Navy had a proven means of rescuing submariners.

1.2.1. Current US Navy Submarine Rescue

The U.S. Navy's current submarine rescue capability is provided by three SRCs and one Deep Submergence Rescue Vehicle (DSRV), Mystic (Figure 1.11). The second DSRV, Avalon, was decommissioned in 2000. The capabilities of the SRC and DSRV are summarized in Table 1.1.

Table 1.1. Summary of SRC and DSRV Capabilities (US Navy, DSU n.d.)

	SRC 21	DSRV 1
Weight	21,600 lbs	76,000 lbs
Displacement	21,550 lbs	82,000 lbs
Crew	2	4
Rescuee Capacity	6	24
Max Depth	850 ft	5,000 ft
Speed	NA	4.1 Knots/8 Hours (Max) 2.5 Knots/14 Hours (Transit) 1.5 Knots/18 Hours (Search)

The SRC (Figure 1.10) operates from a mother vessel in conjunction with the supporting cables, umbilical, air compressors, air banks, control consol, mooring and rigging van, Submarine Rescue Cable Reel, SRC fly away stand and other assorted support equipment. The SRC mode of operation is identical to the original McCann Rescue Chamber.

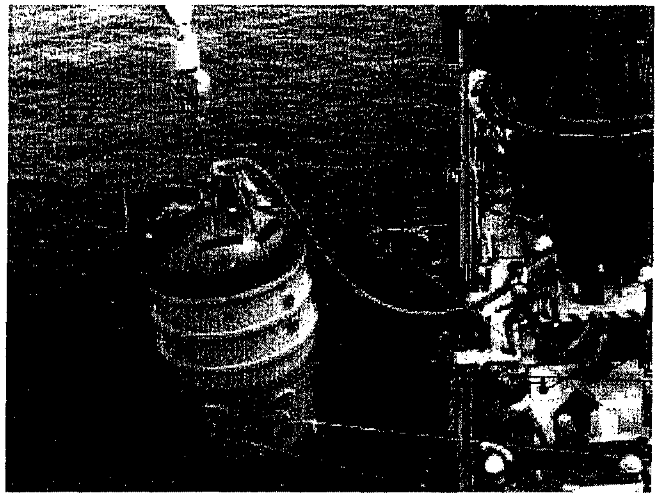

Figure 1.10. Current Submarine Rescue Chamber (US Navy 2000)

DSRV 1 began service in 1971 and is intended "to provide a quick reaction, worldwide, all-weather capability to rescue personnel from disabled submarines at depths up to 2,000 ft." (US Navy, DSU n.d.) DSRV is deployed via a C-5 aircraft from its homeport in San Diego, California (Figure 1.11).

Figure 1.11. DSRV Airlift

After being flown by an Air Force C-5 to the nearest capable port, the DSRV is loaded on a waiting mother submarine for transport to the disabled submarine, shown in Figure 1.12. Once the DSRV is in the vicinity of the disabled submarine, the DSRV pinpoints the location of the disabled submarine with its onboard sonars.

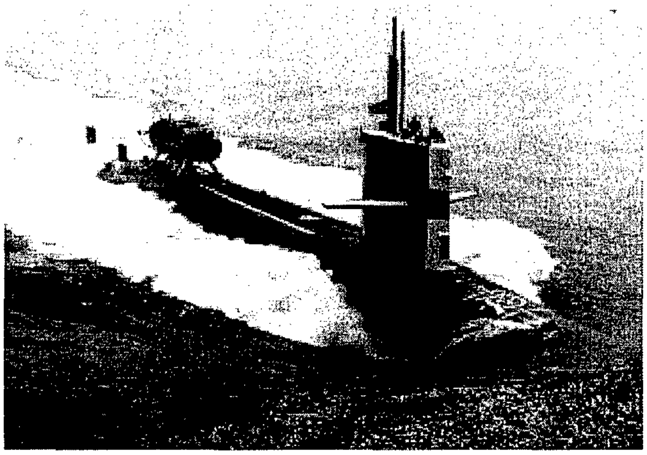

Figure 1.12. Submarine DSRV Transport

The DSRV mates to the disabled submarine using a skirt and hold-down mechanisms similar to the SRC's. Once the connection is secure, the pressure inside the skirt is equalized with the pressure inside the disabled submarine and the hatches are opened. After any rescue supplies are transferred to the disabled submarine (CO_2 scrubbers, food, water, etc.) up to 24 rescuees are transferred to the DSRV, hatches are closed in reverse order, and the DSRV returns to its mother sub. The outer-hull of the DSRV is spun fiberglass, the inner-hull is three connected HY-140 steel spheres, shown in Figure 1.13. Operators are located in the forward most sphere, rescuees and attendants are located in the aft two spheres which can be pressurized as necessary. (GlobalSecurity.org 2002; US Navy, DSU n.d.)

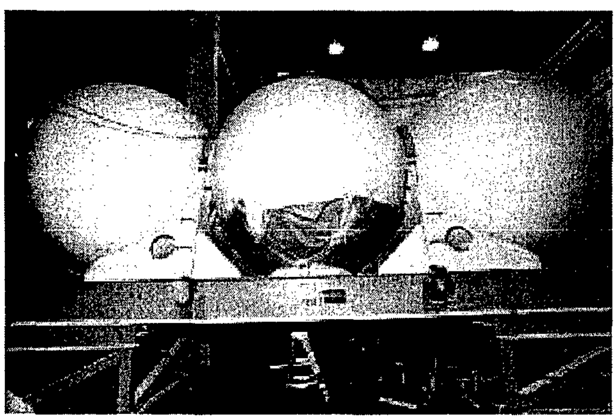

Figure 1.13. DSRV Inner Hull

Although the DSRVs have performed their mission well, the fact that they have to operate from a mother sub or specially adapted surface ship greatly limits how they can be deployed in the event of an actual disabled submarine. Additionally, without a true hyperbaric chamber, they lack the ability to treat and decompress rescuees. To make up for these deficiencies, in 1992 the U.S. Navy issued a Mission Needs Statement stating the requirements for a new submarine rescue system. (NAVSEA 2004, 4)

1.2.2. International Submarine Rescue

Several countries have submarine rescue capability, but many have the same limitations as the DSRV or lack the capacity that would be required for a U.S. system. There is also a NATO Submarine Rescue System, shown in Figure 1.14, in development with many of the same requirements of the SRDRS. Above any others, though, the Australian Navy's REMORA Submarine Rescue Vehicle offers the best glimpse of an operational system that most closely meets the needs of a U.S. system.

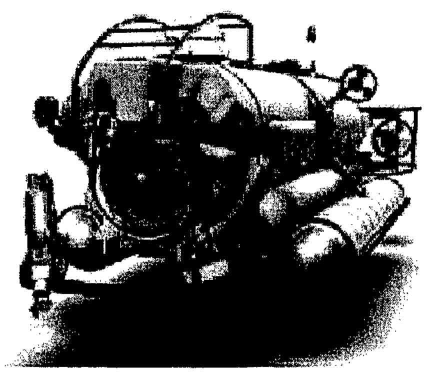

Figure 1.14. Possible NATO Submarine Rescue System (Royal Navy, UK 2005)

Royal Australian Navy REMORA

The Australian Submarine Rescue Vehicle (ASRV) REMORA, shown in Figure 1.15, is a remotely operated vehicle built around a diving bell capable of rescuing up to six people (with one attendant). It is equipped with a trainable mating skirt that can mate with hatches up to 60 deg

from vertical. The REMORA is deployed using a LARS A-Frame (Figure 1.16). It is operated and supported by vans located onboard the mother ship. The support equipment includes two decompression chambers capable of the Transfer Under Pressure (TUP) of personnel under pressure and treating up to 36 people each. The whole system can be packaged in ISO containers, shipped (anywhere in Australia) and installed on a mother ship, "ready to sail," within 72 hours (RAN 2004). Since the ASRV REMORA has been in operation for seven years including use in exercises, it provides a good model for the eventual use and operation of the SRDRS.

Figure 1.15. ASRV REMORA (RAN 2004)

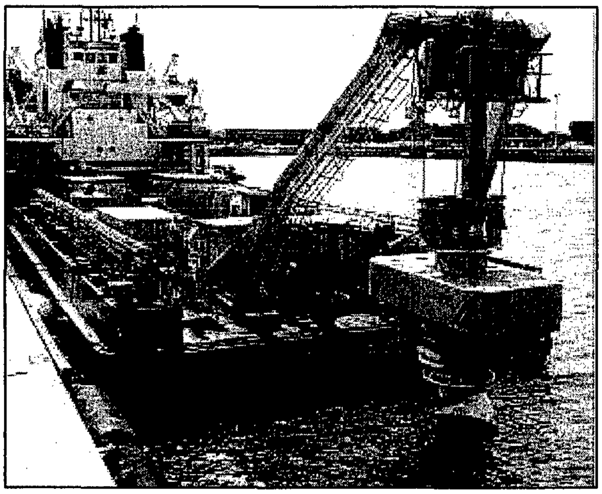

Figure 1.16. REMORA Deployed with LARS (NAVSEA 2004, 20)

1.3. Future US Navy Submarine Rescue: SRDRS

1.3.1. Mission Needs and Operational Requirements

As discussed earlier, the existing SRC and DSRV systems do not have the capability for rapid deployment or treatment of large number of casualties. This shortfall prompted the development of a Mission Needs Statement (MNS) and subsequent Operational Requirements Document (ORD). As summarized in the NAVSEA SRDRS system brief, the general mission requirements include:

- *Worldwide rapid response, not constrained by requirement for dedicated support vessels nor Mother Submarines (MOSUBs)*
- *Operate from VOOs*
- *Perform end-to-end rescue of crew from pressurized disabled submarine*
- *Government Owned/Contractor Operated (GO/CO) maintenance and operations to facilitate crew training & proficiency*
- *Maximize use of COTS [Commercial Off The Shelf] technologies and open software/processor architectures to simplify procurement of spares and the incorporation of future upgrades*
- *System is modular . . . shipping packages optimized for either commercial or military transport* (NAVSEA 2004, 11)

These mission requirements, specific system configuration requirements, and the decision to use the T-ATF as the baseline VOO provided the framework which guided the initial SRDRS designs. With the SRDRS nearing the end of design and construction one critical issue remained: how to select a Vessel of Opportunity.

1.4. The Problem of Selecting a Vessel of Opportunity

In addition to the operational requirements, the SRDRS was designed to a set of engineering standards (US Navy and commercial) all within the constraint of using the T-ATF as a VOO. Because the T-ATF is unlikely to be used as a VOO in an actual rescue, the constraints defined by the T-ATF case serve as a set of minimum requirements for the VOO. Even given that set of VOO requirements, the problem of selecting a VOO from a world of vessels still exists. Potential VOOs can be located and identified by shipping brokers, often the only information that is known about the potential VOOs are the basic vessel characteristics that are part of vessel registers and databases such as the Oilfield Publications, Ltd. Anchor Handling

Tugs and Supply Vessels (OPL-AHTS) database. An example of the data available in this database is shown in Figure 1.17.

VOO2 : Select Query

VesselIndex	VESSEL_Name	LOA(m)	WIDTH(m)	DWT(t)	DECKLENGTH(m)	DECKWIDTH(m)	DECKSTRENGTH(t/m²)	DECKCARGO(t)	DRAUGHT(m)	GT(t)	NT(t)
737	A H Porto Santo	66	15.85	1525	37	12.5	15	1000	6.45	1834	568
2845	A H Portofino	67.7	14.6	1172	32	11	5	680	4.97	1591	477
46	A H San Fruttuoso	73.95	16.9	2059	39.6	14	10	1100	6.85	2725	817
3181	A H Varazze	60.2	13		30	10	5	625	5.97	1141	342
3637	A P Moller TBN 1 z	69.3	20.3								
3514	A W Martin	53.34	13.41		36.5	11.5		863	4.26	99	
874	Aassaf 4501	45	10						3.8	452	148
3391	Abu Al Hasanain	66	11.5						1.7	394	206
630	Abdon Callais	44	11		35.9	9.15		275	3.15	440	132
388	Abdulla Al Fatih	37.6	9.21						3.86	392	117
3635	Abeer Forty	33.53	7.93						1.89	172	61
3639	Abeer Thirteen	33.53	7.93						1.19	169	50
3540	Abeer Thirty Five	41.14	8.56						2.36	254	79
3542	Abeer Thirty Seven	30	8	90					1.2	208	62
3543	Abeer Thirty Six	30	8	90					1.3	208	62
1597	Abeille Flandres	63.28	14.41	1550					7	1577	424
1596	Abeille Languedoc	63.28	14.42	1650					6.69	1605	424
1504	Abordaman	44.75	10.87	598	10	8	5		4.95	480	251
3636	Abir Eleven	33.53	7.62						1.89	153	45
1994	Abu El Hool 4	60.3	11.59	648	24	10.6			4.28	734	307
1523	Acadian Patriot	53.64	11.59	711	29.87	9.14	2.5	370	3.5	199	135
3640	Acamar	39	9.5	750					2.6	386	116
526	Achille	66.4	14	1439	36	11	6	800	5.2	1502	524
1083	Achilino O	32	10						4.6	350	97
2809	Acoustic Pioneer	54.89	12.2	1200	37.8	9.45				282	101
2089	Acqua Chiara	64.30	13.8	1169	37.86	10.59	6	800	4.7	1316	394
395	Activa Gill	80.77	18	2310	57	15	5	2500	4.95	2562	667

Record: 1 of 3586

Figure 1.17. Example of OPL-AHTS Database

Given those basic characteristics, vessels which have been identified as potential VOOs must be quickly evaluated for their adequacy to carry the SRDRS. In order to do that, this thesis will use commercially available computer programs to develop hull geometry based on those characteristics, estimate vessel weight and weight distribution and finally analyze the stability and seakeeping adequacy of the vessel for supporting the SRS. A separate study is examining the issue of judging structural adequacy with respect to detailed scantling information.

1.4.1. Vessel of Opportunity Requirements

The specific requirements which will be used to judge the adequacy of a potential VOO to support the SRS are listed in Table 1.2. The deck geometry requirements are based on explicit requirements from documents in NAVSEA 00C31 *SRS System Documents, Vessel of Opportunity Documents, Volume 9*. The stability requirement uses the "IMO Resolution A.749(18)-3.1 (A.167), General Intact Stability Criteria for All Ships", but other stability criteria can be used if desired. The seakeeping acceleration requirements are based on the John J. McMullen Associates (JJMA) T-ATF seakeeping analysis (JJMA 1996) which provided the basis for the constraints used in the design of the SRDRS.

Table 1.2. Criteria for VOO Adequacy

Parameter	Value
DECK GEOMETRY(NAVSEA 1, 2, 11)	
Deck Length (min)	29.3 m (96 ft)
Deck Width (min)	9.14 m (30 ft)
Deck Cargo (min)	185.5 tonnes (182.6 LT)
Deck Strength (min)	2 tonnes/m^2 (0.19 LT/ft^2 = 2.8 psi)
STABILITY (IMO Resolution A.749(18)-3.1 (A.167), General Intact Stability Criteria for All Ships)	
GZ vs Angle of Heel:	
Area to 30 deg (min)	0.05 m-rad (9.4 ft-deg)
Area to 40 deg (min)	0.09 m-rad (16.92 ft-deg)
Area 30 to 40 deg (min)	0.03 m-rad (5.64 ft-deg)
Angle at Max GZ (min)	25 deg
Max GZ	0.2 m (0.66 ft)
Initial GM (min)	0.15 m (0.49 ft)
SEAKEEPING, up to Sea State 4, accelerations at head of LARS A-Frame at max aft outreach. (John J. McMullen Associates, 7, 8)	
Longitudinal Acceleration	0.20 g
Transverse Acceleration	0.39 g
Vertical Acceleration	0.31 g

1.5. Overview of Proposed Methodology for VOO Analysis and Selection

In order to perform stability and seakeeping analyses using the limited information contained in the OPL-AHTS database, assumptions and estimations will necessarily have to be made regarding the actual properties of the potential VOOs. Some of these estimations will directly influence the development of the hull geometry, weight location and distribution. These assumptions are necessary to perform the required stability and seakeeping analyses. This thesis will attempt to show that the underlying assumptions used in developing the VOO characteristics are based on basic naval architectural principles or typical vessel characteristics. The proposed analysis procedure, summarized in Figure 1.18, begins by verifying the basic deck geometry for the required area to hold the SRS. Next, the hull geometry is generated and used to create a model of the ship including the lightship weight distribution. The ship model is then used as the

starting point for the stability analysis which evaluates the potential VOO against stability criteria at a number of different loading conditions, all with the SRS loading included. Finally, the seakeeping analysis is performed using the ship model that was previously developed.

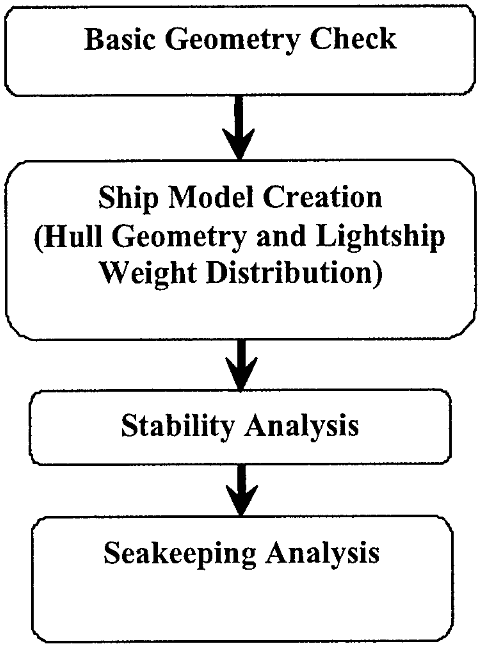

Figure 1.18. VOO Selection Procedure Overview

1.6. Thesis Outline

- Chapter 2. THEORETICAL DEVELOPMENT OF A STABILITY AND SEAKEEPING MODEL – Develops the theoretical and analytical underpinnings of the VOO stability and seakeeping analysis procedure.

- Chapter 3. PROCEDURE FOR THE SELECTION OF A POTENTIAL VOO – Describes the VOO analysis procedure using illustrations and examples from the procedure tutorial of APPENDIX A

- Chapter 4. VERIFICATION OF VOO SELECTION – Compares the results of using the T-ATF in the analysis procedure against the known stability of the T-ATF and two different methods of seakeeping analyses performed on the T-ATF. This chapter also describes a sensitivity analysis performed with the estimated hull coefficients using the T-ATF characteristics and the results of the procedure applied to a larger AHT and deck barge.

- Chapter 5. ANALYSIS OF OPTIONS FOR IMPLEMENTATION OF VOO SELECTION – examines other options for selecting adequate VOOs.

- Chapter 6. CONCLUSIONS AND FUTURE WORK – final observations suggestions for future work and areas of study, and final conclusions

Chapter 2. THEORETICAL DEVELOPMENT OF A STABILITY AND SEAKEEPING MODEL

Since the whole deployment process of the SRDRS must happen quickly, potential VOOs must be rapidly identified and evaluated for suitability. This thesis is concerned with the process of evaluating the stability and seakeeping of potential VOOs. Although empirical models exist for analyzing the stability and seakeeping performance of ships, modern computer programs which can perform a full, physics based analysis are both readily available and can quickly analyze a vessel. These analysis programs, and the programs which I will use for this thesis require accurate hull geometry and weight distribution. Unfortunately, the vessel information that may be available for analysis is likely limited to gross hull and weight characteristics. As with many aspects of this analysis procedure, limited vessel information will lead to an adequate model that can be analyzed only by making key assumptions about hull geometry and weight distributions. This chapter will discuss those assumptions within the context of developing the theory underlying the stability and seakeeping analyses.

2.1. Ship Geometry

As discussed above, developing a vessel's basic hull geometry is the first step in being able to perform stability and seakeeping analyses. Since the process this thesis proposes will develop hull geometry from limited basic information, only primary hull geometry will be developed and hull appendages ignored. I expect that any differences in hull geometry or appendages between the model and actual vessel will have a small impact on either the stability or seakeeping analysis. I will examine and verify this hypothesis in Chapter 4.

2.1.1. Hull Geometry and the Development of Hull Offsets

The basic hull characteristics that will be used are illustrated in Figure 2.1 and defined in Table 2.1.

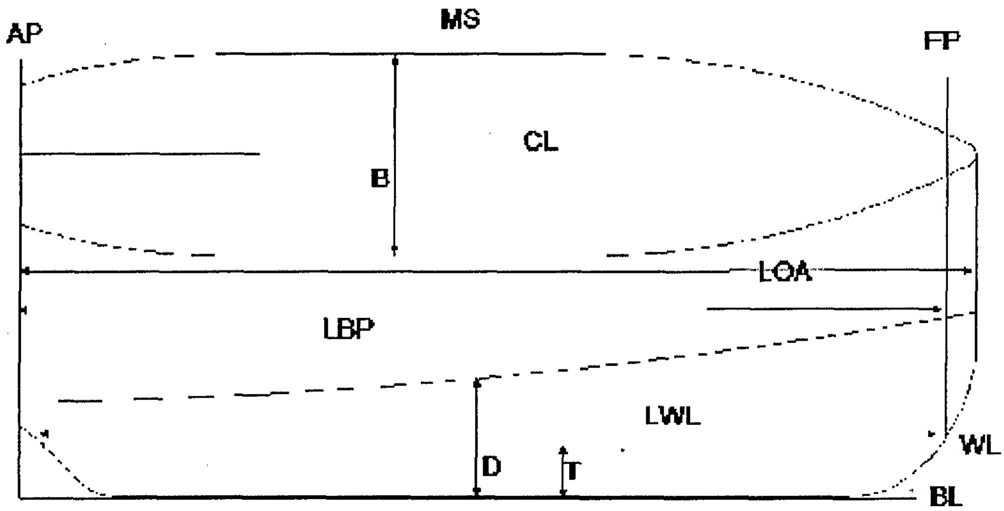

Figure 2.1. Basic Hull Characteristics

Table 2.1. Basic Hull Characteristics

AP	After Perpendicular
B	Beam
BL	Baseline
CL	Center Line
D	Depth
FP	Forward Perpendicular
LBP	Length Between Perpendiculars
LOA	Length Over-All
LWL	Length on Water Line
MS	Midships, also indicated by the symbol: 
T	Draft
WL	Water Line

The following equations (Table 2.2) define the basic coefficients used to describe a hull where ? is the displacement of a vessel at a given draft and ∇ is the volume of displaced water at a given draft:

Table 2.2. Coefficients of Form (SNAME 1988, 1: 18-19)

Block Coefficient, C_B	$C_B = \dfrac{V}{L \cdot B \cdot T}$	**Equation 2.1**
Midship Coefficient, C_M where A_M = immersed area of the midships section	$C_M = \dfrac{A_M}{B \cdot T}$	**Equation 2.2**
Prismatic Coefficient, C_P	$C_P = \dfrac{V}{L \cdot B \cdot T \cdot C_M} = \dfrac{C_B}{C_M}$	**Equation 2.3**
Waterplane Coefficient, C_{WP} Where A_{WP} = waterplane area	$C_{WP} = \dfrac{A_{WP}}{B \cdot T}$	**Equation 2.4**

The procedure of developing the geometry of the VOO's hull is not unlike the design process for a new hull. The goal is to develop the overall hull geometry from limited information. The hull geometry is described by hull offsets which are the half-breadth distance of the hull from midship at predefined stations (longitudinal) and waterlines (vertical). While there are many options available for developing hull offsets, this process will use the U.S. Navy's HULLGEN program which is contained in the ASSET program. HULLGEN utilizes a vessel's principal dimensions to create a polynomial representation of the desired hull and then converts this to offsets (NSWC-CD 2003, 7.0). The principal dimensions that HULLGEN uses include: LBP, depth at stations 0, 10 and 20, C_P, C_X (here C_X is the same as C_M for generating the hull geometry of this type in ASSET) and C_{WP}. Using these principal dimensions, HULLGEN then defines fourteen "control curves" including sectional area curve, design

waterline curve, sheer profile curve, stem profile curve, stern profile curve, etc… (NSWC-CD 7.2). The control curves are created from various order polynomials using the principal dimensions as inputs. For example, the section area curve uses the seventh-order polynomial shown in Equation 2.5:

$$Y = C_0 + C_1X + C_2X^2 + \ldots + C_7X^7$$

Equation 2.5. (NSWC-CD 2003, 7.2.1.1.1)

where Y is the section area, X is the non-dimensional section, and the coefficients are derived by solving the section area polynomial for eight different boundary conditions that are either determined by the required geometry or the principal dimensions. Each of the fourteen control curves are determined in a similar fashion but with different order polynomials and different boundary conditions. These control curves are then used to derive the actual hull geometry.

The hull section geometry below the waterline is determined using Equation 2.6:

$$Y = C_0 + C_1Z + C_2Z^2 + C_3(Z+1)^{-1} + C_4(Z+0.001)^{1/2}$$

Equation 2.6. (NSWC-CD 2003, 7.3-1)

where Z is the height from BL, Y is the distance from CL, and the five coefficients are determined by solving five linear simultaneous equations of the polynomial using various boundary conditions (slopes or areas) determined by the control curves (NSWC-CD 2003, 7.3-1). Hull section geometry above the waterline is determined using Equation 2.7:

$$Y = C_0 + C_1Z + C_2Z^2 + C_3Z^3$$

Equation 2.7. (NSWC-CD 2003, 7.3.2.1.2)

where Z is the height from BL, Y is the distance from CL, and the four coefficients are again determined by solving four linear simultaneous equations of the polynomial using various boundary conditions (slopes or areas) determined by the control curves (NSWC-CD 2003, 7.3.2.1.2).

With the hull geometry curves now determined, HULLGEN creates the offsets based on the desired number of stations and offsets.

With a parent hull created, hull offsets using the same hull coefficients but having differing length and beam can also be calculated without changing the underlying geometry (SNAME 1988, 21). HULLGEN can utilize a parent hull and scale a hull on length and beam. HULLGEN can also revise the parent offsets to achieve hulls with a slightly different C_P, and C_M.

2.2. Stability

The procedure proposed in this thesis uses the computer program POSSE 4 to solve and evaluate the potential VOO's stability. The following discussion briefly reviews ship hydrostatics and stability as well as how stability is evaluated and judged within POSSE 4.

2.2.1. General Hydrostatics and Ship Stability Background

According to Archimedes principle a floating ship of a given weight will displace an equal weight of water (SNAME 1988, 1: 16). The weight, W, of displaced water (and the weight of the ship) is given by Equation 2.8, where ? is the density of water, g is the acceleration of gravity, and ∇ is the volume of displaced water (also the volume of the ship below the waterline):

$$W = \rho g \nabla$$

Equation 2.8. (SNAME 1988, 1: 16)

In mass terms, the displacement of the ship, ?, is given by Equation 2.9:

$$\Delta = \rho \nabla$$

Equation 2.9. (SNAME 1988, 1: 16)

The buoyant force, which keeps the ship floating, acts through the centroid of the underwater volume. The transverse cross-section shown in Figure 2.2 illustrates the force of a ship of weight, W, acting through the center of gravity, G, being counteracted by an equal buoyant force, W, through the center of buoyancy, B.

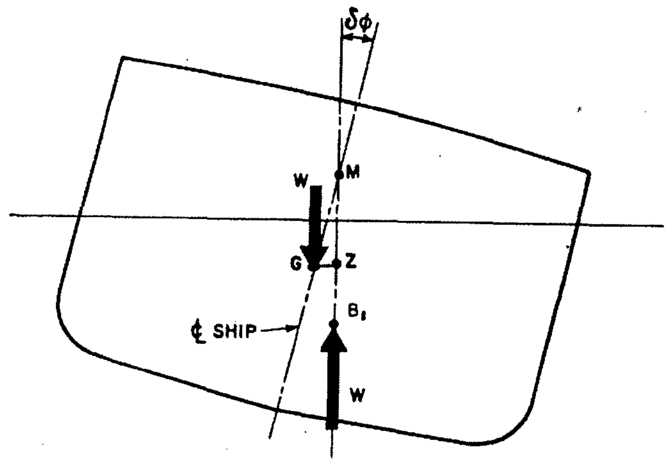

Figure 2.2. Ship Metacenter (SNAME 1988, 1: 71)

Figure 2.2 also shows the ship rotated by angle of *df* causing the buoyant force to act as a restoring moment with moment arm, *GZ*. The effect of this restoring moment is to cause the ship to move like a pendulum with the axis of rotation at *M*, the metacenter. Although the metacenter moves as the underwater volume changes, for small angles of displacement it remains in approximately the same place so that *GZ* is given by Equation 2.10, where GM is the distance from the center of gravity to the metacenter:

$$\overline{GZ} \approx \overline{GM} \sin \delta\phi$$

Equation 2.10 (SNAME 1988, 1: 71)

The metacentric radius, *BM*, is given by Equation 2.11 where I_T is the moment of inertia of the waterplane about the ship's centerline:

$$\overline{BM} = \frac{I_T}{\nabla}$$

Equation 2.11 (SNAME 1988, 1: 72)

Assuming the center of gravity, KG, metacentric height, KM, and the height of the center of buoyancy, KB, are known, geometry yields the following relations in Equation 2.12:

$$\begin{aligned}\overline{GM} &= \overline{KM} - \overline{KG} \\ &= \overline{KB} + \overline{BM} - \overline{KG}\end{aligned}$$

Equation 2.12 (SNAME 1988, 1: 72)

The same relations hold true for longitudinal stability, but with different quantities because of the different underwater shape as shown in Figure 2.3.

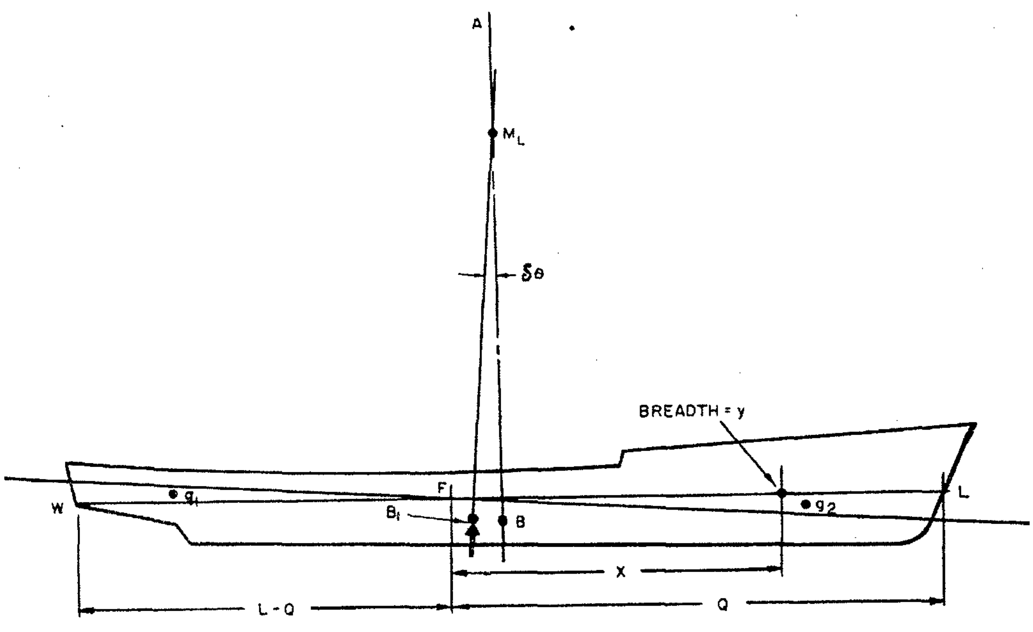

Figure 2.3. Longitudinal Metacenter

As with the transverse BM, the longitudinal BM_L is given by Equation 2.13, where I_L is the moment of inertia of the underwater area around midships through the center of flotation.

$$\overline{BM}_L = \frac{I_L}{\nabla}$$

Equation 2.13 (SNAME 1988, 1: 72)

A convenient measure of longitudinal stability is the "Moment to Trim one Inch" (*MTI*) defined by Equation 2.14:

$$MTI = \frac{W\overline{GM_L}}{12L} ton \cdot ft \approx \frac{\rho g I_L}{12L} ton \cdot ft$$

Equation 2.14 (SNAME 1988, 1: 73)

In practice, these measures of stability are found by referring to "Curves of Form," or "hydrostatic curves" which relate the draft of the vessel to the value of the variable. The hydrostatic curves are derived by integrating various curves of form (e.g., section area curve at a waterline) to find the underwater area or volume required for the definition of the stability parameter (KM, KB, LCF, LCB, C_P, C_X, MT1, etc...). Computer programs, such as POSSE 4, can develop the section area curves, hydrostatic curves and cross curves of stability (for stability parameters such as GM, GZ, etc) numerically. When combined with developing and applying a weight distribution for LCG and VCG (or shifted KG, defined in Equation 2.15), POSSE is able to solve for any desired intact stability parameter in real-time.

$$\overline{KG_1} = \frac{\Delta_0 \overline{KG_0} + w_1 \overline{Kg_1}}{\Delta_1}$$

Equation 2.15 (Gillmer and Johnson 1982, 120)

2.2.2. Application of Stability Criteria

Stability criteria mandated by governmental or international organizations are based on establishing a "suitable metacentric height" for a number of different conditions including

different voyage loading conditions, wind loading, turning heel, etc, for both intact and damage conditions. According to *PNA Vol. I*, minimum GM is dictated by the following concerns

> *(a) It should be large enough in passenger ships to prevent capsizing or an excessive list in case of flooding a portion of the ship during an accident ...*
> *(b) It should be large enough to prevent listing to unpleasant or dangerous angles in case all passengers crowd to one side. This may require considerable GM in light-displacement ships, such as excursion steamers carrying large numbers of passengers.*
> *(c) It should be large enough to minimize the possibility of a serious list under pressure from strong beam winds.* (SNAME 1988, 1: 77)

Given those concerns, both the International Maritime Organization (IMO) and U.S. Coast Guard (through the Code of Federal Regulations (CFR)) have established minimum criteria for each vessel type for intact and damaged stability at various types of loading conditions. Any of these criteria can be applied within POSSE to be able to judge a vessel's adequacy for stability. However, this proposed procedure only develops basic hull geometry and basic weight distribution, and so only basic intact stability criteria can be applied. No accounting for free surface effect can be made since tankage is not developed. Criteria which rely on knowledge of internal subdivision (damaged stability) or topside area (wind heel stability) cannot be applied. The procedure proposed in this thesis uses "IMO Resolution A.749(18)-3.1 (A.167), General Intact Stability Criteria for All Ships" to judge stability. The specifics of the criteria and how they are applied in POSSE are addressed in the discussion of the procedure itself.

2.3. Seakeeping

Estimating and predicting the motions of a vessel in a given sea state is still a difficult problem even given complete knowledge of a vessel and the seas that vessel encounters. Despite that lack of detailed information, this procedure will utilize the vessel information developed for the stability analysis to predict the ship motions. The VOO seakeeping analysis will use the hull geometry and weight distributions that are developed for the stability analysis as inputs to the POSSE Ship Motions Program (SMP) in order to simulate and predict the response of the potential VOO in a seaway.

2.3.1. Sea State

The developed sea state can be summarized by assuming local ocean waves can be represented by a superposition of many regular waves, each with their own period and height (SNAME 1989, III: 8). The total wave height, ?, is given by Equation 2.16, where A_j is the wave amplitude, $?_j$ is the circular frequency, k_j is the wave number, and e_j is the random phase angle.

$$\zeta = \sum_{j=1}^{N} A_j \sin(\omega_j t - k_j x + \varepsilon_j)$$

Equation 2.16. (Faltinsen 1990, 23)

The random phase angle, e_j, is uniformly distributed between 0 and 2p. And, $?_j$ and k_j are related by the dispersion relation: $?^2=k/g$. Finally, the amplitude, A_j, can be described by an empirically derived sea spectrum, *S(?)*, Equation 2.17, where ? ? is the constant difference between each component frequency of the spectrum. (Faltinsen 1990, 23)

$$\tfrac{1}{2} A_j^2 = S(\omega_j) \cdot \Delta\omega$$

Equation 2.17. (Faltinsen 1990, 23)

The sea spectra, *S(?)*, are based on "short term" observations of various ocean areas. Many different spectra have been developed including Pierson-Moskowitz from the International Ship Structures Conference (ISSC) and the JONSWAP (Joint North Sea Wave Project) developed by the 17th International Tow Tank Conference (ITTC)). These spectra, with their applicable statistical descriptions and inputs, are defined in *Sea Loads on Ships and Offshore Structures* (Faltinsen 1990) and *PNA, Vol. III.* The Pierson-Moskowitz, JONSWAP and many other spectra are already part of and can be used for analysis in POSSE SMP. This procedure will use the Bretschneider spectrum (Figure 2.4) since it requires no additional statistical input other than significant wave height and period.

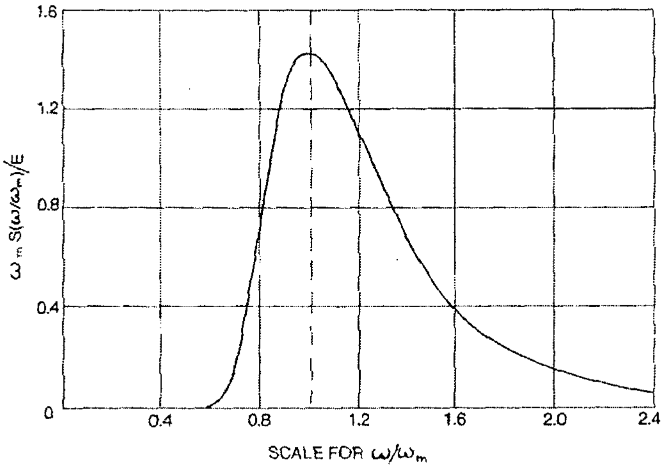

Figure 2.4 Normalized Bretschneider Spectrum (SNAME 1989, 3: 37)

The Bretschneider spectrum assumes it is reasonable to approximate a broad spectrum seastate without using as many statistical descriptors as some other spectra. The exceptions to the assumption are cases of unusual spectrum shape such as specific storm swells. · However, for most general cases and ship seakeeping analyses, the Bretschneider spectrum yields good results (SNAME 1989, 3: 38). Equation 2.18 gives a simplified version of the Bretschneider spectrum, *S(?)*, where *?* is the frequency, *?* $_m$ is the modal frequency, and *?* is the significant wave height:

$$S(\omega) = \frac{1.25}{4} \frac{\omega_m^4}{\omega} \zeta^2 e^{-1.25\left(\frac{\omega_m}{\omega}\right)^4}$$

Equation 2.18. (Techet 2005, 9)

When using the Bretschneider spectrum, POSSE Ship Motions Program (SMP) calculates the modal frequency for the desired significant wave height and wave period (inputs).

2.3.2. Ship Motions – Theory

Describing ship motions in a seaway begins with the definitions of the ship motion in the cardinal directions (shown in Figure 2.5): displacements in the *(x, y, z)* directions (surge, sway, heave) are indicated respectively by the numbers *(1, 2, 3)*, the rotational displacements around the axes of *(x, y, z)* (roll, pitch, yaw) are indicated respectively by *(4, 5, 6)*.

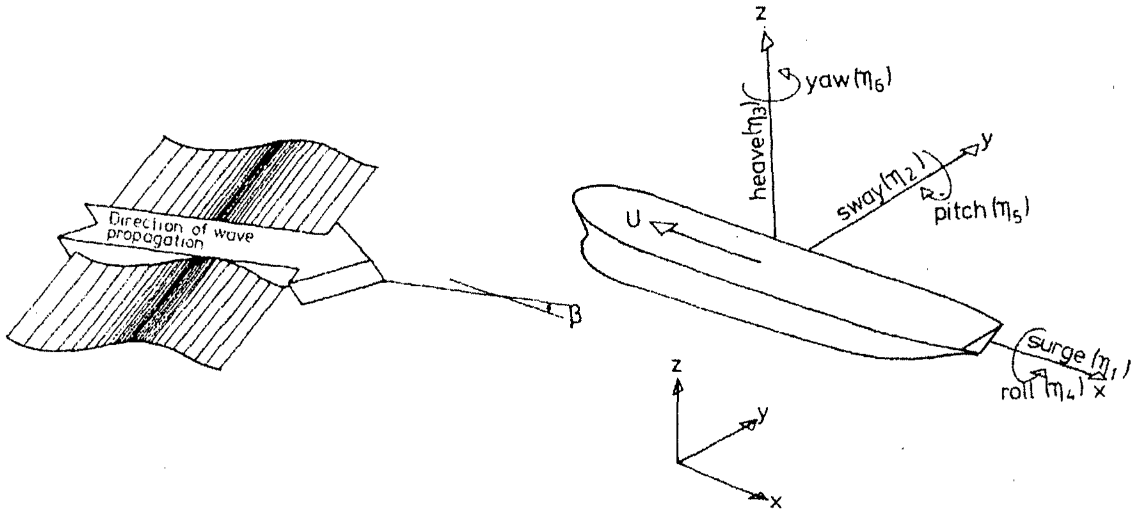

Figure 2.5. Sign conventions for ship motions (Faltinsen 1990, 41)

The linearized Euler body force equation is given by Equation 2.19, where $?_{jk}$ are the individual inertia elements for each direction, $\ddot{\eta}_k$ are the accelerations in each direction, and $\mathbf{F}_j(t)$ are the forces and moments acting on the body in each direction.

$$\sum_{k=1}^{6} \Delta_{jk} \ddot{\eta}_k(t) = \mathbf{F}_j(t) \qquad j=1,2,\ldots 6$$

Equation 2.19. (SNAME 1989, 3: 46)

Abkowitz (1969) linearized these equations for the case of a ship with lateral symmetry, yielding the equations of Table 2.3:

Table 2.3. Linearized Equations of Motion (SNAME 1989, 3: 46)

surge	$\Delta(\ddot{\eta}_1 + \bar{z}_c\ddot{\eta}_5) = \mathbf{F}_1$
sway	$\Delta(\ddot{\eta}_2 - \bar{z}_c\ddot{\eta}_4 + \bar{x}_c\ddot{\eta}_6) = \mathbf{F}_2$
heave	$\Delta(\ddot{\eta}_3 - \bar{x}_c\ddot{\eta}_5) = \mathbf{F}_3$
roll	$I_{44}\ddot{\eta}_4 - I_{46}\ddot{\eta}_6 - \Delta\bar{z}_c\ddot{\eta}_2) = \mathbf{F}_4$
pitch	$I_{55}\ddot{\eta}_5 - \Delta\{\bar{z}_c\ddot{\eta}_1 + \bar{x}_c\ddot{\eta}_3\} = \mathbf{F}_5$
yaw	$I_{66}\ddot{\eta}_6 - I_{64}\ddot{\eta}_4 - \Delta\bar{x}_c\ddot{\eta}_2 = \mathbf{F}_6$

where $\mathbf{F}_{1,2,3}$ are the forces in each direction; $\mathbf{F}_{4,5,6}$ are the moments in each direction; **?** is the vessel mass; $\bar{x}_c$ and $\bar{z}_c$ are the coordinates of the center of gravity in the body-axis coordinate system(non-moving with respect to the ship $(\bar{x}, \bar{y}, \bar{z})$); $I_{44}, I_{46}, I_{55}, I_{66}$, and I_{64} are all moments of inertia about their respective axes; and $\ddot{\eta}_k$ are the accelerations in each direction. Full definitions and development of what follows is shown in *PNA Vol. III*, Sec. 3. Each $\mathbf{F}_j$ can be broken down into a gravitational component, $\mathbf{F}_{Gj}$, and a fluid force component, $\mathbf{F}_{Hj}$:

$$\mathbf{F}_j(t) = \underset{j=1,2,\dots 6}{\mathbf{F}_{Gj}} + \mathbf{F}_{Hj}$$

Figure 2.6. (SNAME 1989, 3: 47)

The fluid force is given by Equation 2.19, where n_j is the unit normal to the surface of the hull, P is the fluid pressure on the hull, and s is the underwater hull surface area.

$$\mathbf{F}_{Hj} = \iint_{S'} P n_j ds$$

Figure 2.7. (SNAME 1989, 3: 47)

Assuming inviscid, irrotational flow, the pressure at any point on the hull, P, is given by Bernoulli's equation, Equation 2.20, where *?* is the fluid density, $\nabla \mathbf{F}$ is the total fluid velocity, and U_0 is the speed of the ship.

$$P = \tfrac{1}{2}\rho U_0^2 - \rho\frac{\partial\Phi}{\partial t} - \tfrac{1}{2}\rho(\nabla\Phi \times \nabla\Phi) - \rho g z$$

Equation 2.20. (SNAME 1989, 3: 49)

Thus, the total fluid force (Equation 2.21) on the ship is found by a combination of the hydrostatic force, F_{HSj} (Equation 2.22) and the hydrodynamic force, F_{HDj} (Equation 2.23) (SNAME 1989, 3: 48).

$$\mathbf{F}_{Hj} = \mathbf{F}_{HSj} + \mathbf{F}_{HDj}$$

Equation 2.21.

$$\mathbf{F}_{HSj} = -\rho g \iint_{S'} z n_j ds$$

Equation 2.22.

$$\mathbf{F}_{HDj} = -\rho \iint_{S'} \left(\tfrac{1}{2} U_0^2 - \frac{\partial \Phi}{\partial t} - \tfrac{1}{2}(\nabla\Phi \times \nabla\Phi) \right) n_j ds$$

Equation 2.23.

Solving for the hydrodynamic forces requires solving the total velocity potential for the fluid flow **F** (x,y,z,t) by assuming it is a combination of both steady and unsteady potential. While this is discussed in detail in *PNA Vol. III Sec. 3* (48-60) with full development of all terms of the hydrostatic and hydrodynamic force equations, it is important to be aware of the constituent forces which contribute to solving for the potential field. These forces, and the simplifications which allow for them to be solved for the two dimensional case, are what enable rapid computation of ship motions using strip theory. The steady potential essentially consists of those forces which result from the forward motion of the ship in stillwater and are not time dependent (wave resistance). The unsteady potential is a combination of the incident wave potential, the diffracted wave potential and the radiated wave potential. The incident wave potential are the forces that result from the integrated pressure of the applied sea wave over the hull: the Froude Krylov force. The diffracted wave potential results from the forces which develop from the scattering of incident waves. The radiated wave potential comes from a combination of the damping and added mass forces that result from a body moving or oscillating in a fluid. Each of these potentials are independent and can be superposed to develop the full velocity potential field. The "linearized equations of motion" or six coupled, linear equations for the six unknown complex amplitudes, $\bar{\eta}_k$, are thus given by Equation 2.24:

$$\sum_{k=1}^{6}[-\omega_e^2(\Delta_{jk} + A_{jk}) + i\omega_e B_{jk}]\cdot\overline{\eta}_k = \mathbf{F}_j^I + \mathbf{F}_j^D \qquad j=1,2,...6$$

Equation 2.24. (SNAME 1989, 3: 51)

where the left-hand side of the equation contains all the hydrostatic restoring forces and radiation forces: ?$_{jk}$ is the mass matrix, C_{jk} is the hydrostatic restoring force coefficient matrix, A_{jk} is the added mass matrix, and B_{jk} is the damping matrix. The right-hand side of the equation, $\mathbf{F}_j^I + \mathbf{F}_j^D$, are the incident wave and diffraction components of the "exciting force." The frequency of wave encounter, ? $_e$, is given by Equation 2.25, where ? $_0$ is natural frequency, U_0 is the ship speed, and μ is the angle at which the ship is moving relative to the seas:

$$\omega_e = \omega_0 - \frac{\omega_0}{g} U_0 \cos\mu$$

Equation 2.25. (SNAME 1989, 3: 46)

At this point all the elements are now seemingly in place to solve for the motion of the ship, $\overline{\eta}_k$, by solving the six simultaneous equations of motion using the mass, hydrostatic restoring force coefficient, added mass and damping matrices, and the exciting forces. While solving for the mass matrix, hydrostatic restoring forces and the incident wave forces can be readily performed, calculation of the added mass coefficient and damping coefficient matrices as well as the diffraction forces are much more difficult (SNAME 1989, 3: 53). One way of overcoming these difficulties in practice is to break the problem up into several smaller, two-dimensional hydrodynamic problems which can be more readily solved and integrated to arrive at the final full response solution. This "strip theory" is graphically illustrated in Figure 2.8. This is the essence of strip theory and the underlying routines of POSSE Ship Motions Program

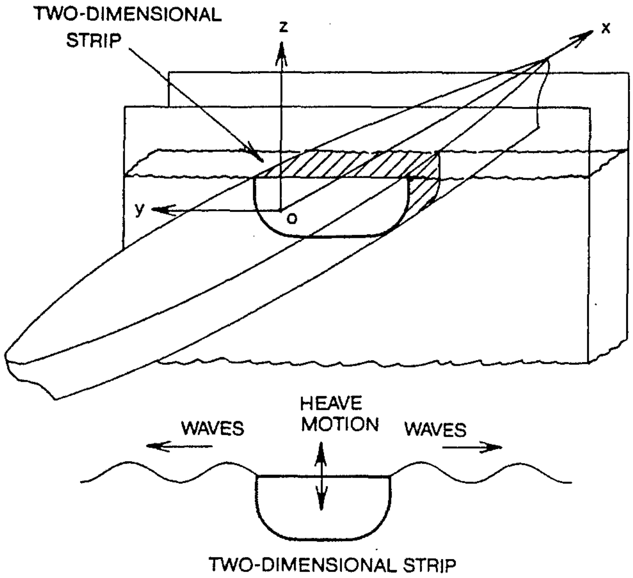

Figure 2.8. Graphic Representation of Strip Theory (SNAME 1989, 3: 52)

Strip theory makes two major assumptions: first, the ship in question can be treated as a "slender body" insomuch as the length is much greater than beam or depth (draft) and the change in the transverse dimensions is gradual over the length; and, second, the speed in question is relatively low (but not zero) which allows the assumption of two dimensional flow over the strip.

Solving for the added mass and damping force coefficients starts by defining the complex force coefficient, T_{jk}, within the context of the radiated hydrodynamic, $\mathbf{F}_{Rj}$, (the combination of the Froude-Krylov, diffracted and radiated forces all make up the total hydrodynamic force on the body) and is shown in Equation 2.26 where ϕ_k is the radiation potential.

$$\mathbf{F}_{Rj} = \sum_{k=1}^{6} T_{jk} \overline{\eta}_k e^{i\omega_e t}$$

$$\textbf{where} \quad T_{jk} = -\rho \iint_S n_j \left(i\omega_e - U_0 \frac{\partial}{\partial x} \right) \phi_k \, ds$$

Equation 2.26. (SNAME 1989, 3: 50)

The added mass and damping force coefficients are found by solving the complex force coefficients, T_{jk}, with applied boundary conditions of the radiation potential, ϕ_k, at the free

surface, hull surface and infinity, for each strip. The total added mass and damping force coefficients are found by integrating the results along the length of the ship (Figure 2.9).

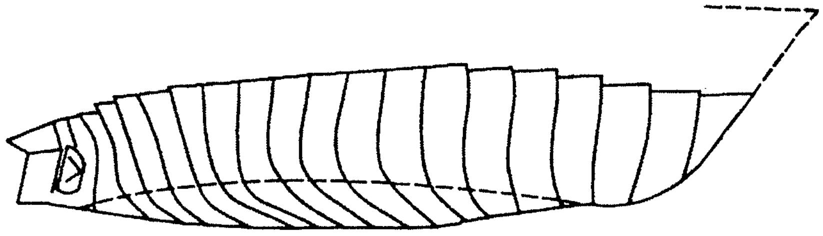

Figure 2.9. Graphic Representation of Strip Theory (Faltinsen 1990, 50)

The exciting forces are solved for each strip by starting first with the Froude-Krylov forces, F_j^I (Equation 2.27), and performing the line integral at each "cross-section" (strip) using slender body approximations for the unit normals down the length of the ship (see SNAME 1989, 3: 55-58).

$$F_j^I = -\rho \iint n_j \left(i\omega_e - U_0 \frac{\partial}{\partial x} \right) \left(\frac{ig\overline{\zeta}}{\omega_0} e^{-ik(x\cos\mu + y\sin\mu)} e^{kz} \right) ds$$

Equation 2.27. (SNAME 1989, 3: 58)

The diffraction exciting forces, F_j^D, are found by Green's Theorem with applied body boundary conditions. Using "Haskind relations" (SNAME 1989: 58), F_j^D is reduced to :

$$F_j^D = \int_L e^{-ikx\cos\mu} h_j(x) dx \qquad j = 1,2,3,4$$

$$F_5^D = \int_L e^{-ikx\cos\mu} \left(x + \frac{U_0}{i\omega_e} \right) h_3(x) dx$$

$$F_6^D = \int_L e^{-ikx\cos\mu} \left(x + \frac{U_0}{i\omega_e} \right) h_2(x) dx$$

Equation 2.28. (SNAME 1989, 3:58)

where "sectional diffraction exciting force", $h_j(x)$, is defined as Equation 2.29:

$$h_j(x) = \rho\overline{\zeta}\omega_0 \int_{Cx} (iN_3 + N_1 \cos\mu + N_2 \sin\mu) \times e^{-iky\sin\mu} e^{kz} \psi_k(y,z) dl \qquad j = 1,2,3,4$$

Equation 2.29. (SNAME 1989, 3:58)

and $\psi_k(y,z)$ is the velocity potential for a cylinder with cross-section approximately equal to the station ship cross-section (Cx). The exciting forces are then brought together with the hydrostatic restoring, added mass, and damping force results in order to solve for the complete ship response in all six degrees of freedom.

2.3.3. Ship Motions in a Seaway

The full ship motion response in a sea state can now be found by solving for the amplitude of response, $\overline{\eta}_j(\omega_e,\mu;U_0)$ (where U_0 is the constant ship speed), in the developed sea spectrum $S_\zeta(\omega)$ using statistical methods. Instead of solving for the ship motion directly, the transfer function, or Response Amplitude Operator (RAO) indicated by $|\overline{\eta}_j(\omega_e,\mu;U_0)|$, is used. The encountered sea spectrum, $S_\zeta(\omega_e;\mu_0,U_0)$, is given by Equation 2.30, where the encounter frequency, ω_e, is now defined by Equation 2.31.

$$S_\zeta(\omega_e;\mu_0,U_0)=\frac{S_\zeta(\omega)}{|1-(2\omega U_0/g)\cos\mu_0|}$$

Equation 2.30. (SNAME 1989, 3: 87)

$$\omega_e=\left|\omega-\frac{\omega^2U_0}{g}\cos\mu_0\right|$$

Equation 2.31. (SNAME 1989, 3: 87)

The full response spectrum, S_j^F, is given by :

$$S_j^F = \left|\overline{\eta}_j^I(\omega_e, \mu; U_0)\right|^2 S^I(\omega_e, \mu; U_0) + \\ \left|\overline{\eta}_j^{II}(\omega_e, \mu; U_0)\right|^2 S^{II}(\omega_e, \mu; U_0) + \\ \left|\overline{\eta}_j^{III}(\omega_e, \mu; U_0)\right|^2 S^{III}(\omega_e, \mu; U_0)$$

Equation 2.32. (SNAME 1989, 3: 88)

where ω_e is now divided into three regions to account for the sign changes in the encounter frequency: region I, $0 < \omega_e \le \frac{g}{2U_0 \cos \mu_0}$; region II $\frac{g}{2U_0 \cos \mu_0} < \omega_e \le \frac{g}{U_0 \cos \mu_0}$ (both I and II the waves are overtaking the ship); and region III $\frac{g}{U_0 \cos \mu_0} < \omega_e \le \infty$ (where the ship is overtaking the waves). For actual response analysis, the statistical moments of the response spectrum are used, m_n, Equation 2.33.

$$m_n = \int_0^{\infty} (\omega_e)^n S_j(\omega_e) d\omega_e$$

Equation 2.33. (SNAME 1989, 3: 88)

where m_0 is the variance of displacement, m_2 is the variance of the velocity, and m_4 is the variance of acceleration in the each of the j=1,2...6 directions. The probability density function of the response, $p(\overline{\eta}_j)$, is given by Equation 2.34:

$$p(\overline{\eta}_j) = \frac{\overline{\eta}_j}{4m_n} e^{\frac{-\overline{\eta}_j^2}{8m_n}}$$

Equation 2.34.

Based on $p(\overline{\eta}_j)$, some of the statistics for response maxima are summarized in Table 2.4.

Table 2.4. Summary of Statistical Response Maxima (SNAME 1998, 3: 91)

Average Response Amplitude	$\langle \overline{\eta}_j \rangle = 1.25\sqrt{m_0}$
Significant Response Amplitude	$\langle \overline{\eta}_j \rangle = 1.25\sqrt{m_0}$
Greatest Response Expected in N independent observations:	
N=100	$\langle \overline{\eta}_j \rangle = 3.25\sqrt{m_0}$
N=1000	$\langle \overline{\eta}_j \rangle = 3.85\sqrt{m_0}$
N=10,000	$\langle \overline{\eta}_j \rangle = 4.45\sqrt{m_0}$

2.3.4. Assessing Ship Motion Response

Although pure RAOs could be used to judge the basic ship motions of a potential VOO, the components of the SRS, specifically the LARS A-frame and associated foundations were designed to withstand maximum accelerations that were based on an initial seakeeping study of the T-ATF for motions at the LARS point. Not only will different potential VOOs have different seakeeping responses, but the simple geometric differences will result in different kinematic translations of the response motions. POSSE SMP can solve for both the ship motions response at the center of gravity and the motions at any desired point.

Chapter 3. PROCEDURE FOR THE SELECTION OF A POTENTIAL VOO

3.1. Introduction

This section details the procedure for analyzing and judging the adequacy of potential VOOs, in step by step fashion: the VOO Adequacy Analysis Procedure (VAAP). This procedure, summarized in Figure 3.1, first creates the hull offsets and the POSSE ship model and then analyzes the potential VOO for stability and seakeeping. The full procedure is detailed in a step-by-step numerical tutorial in APPENDIX A.

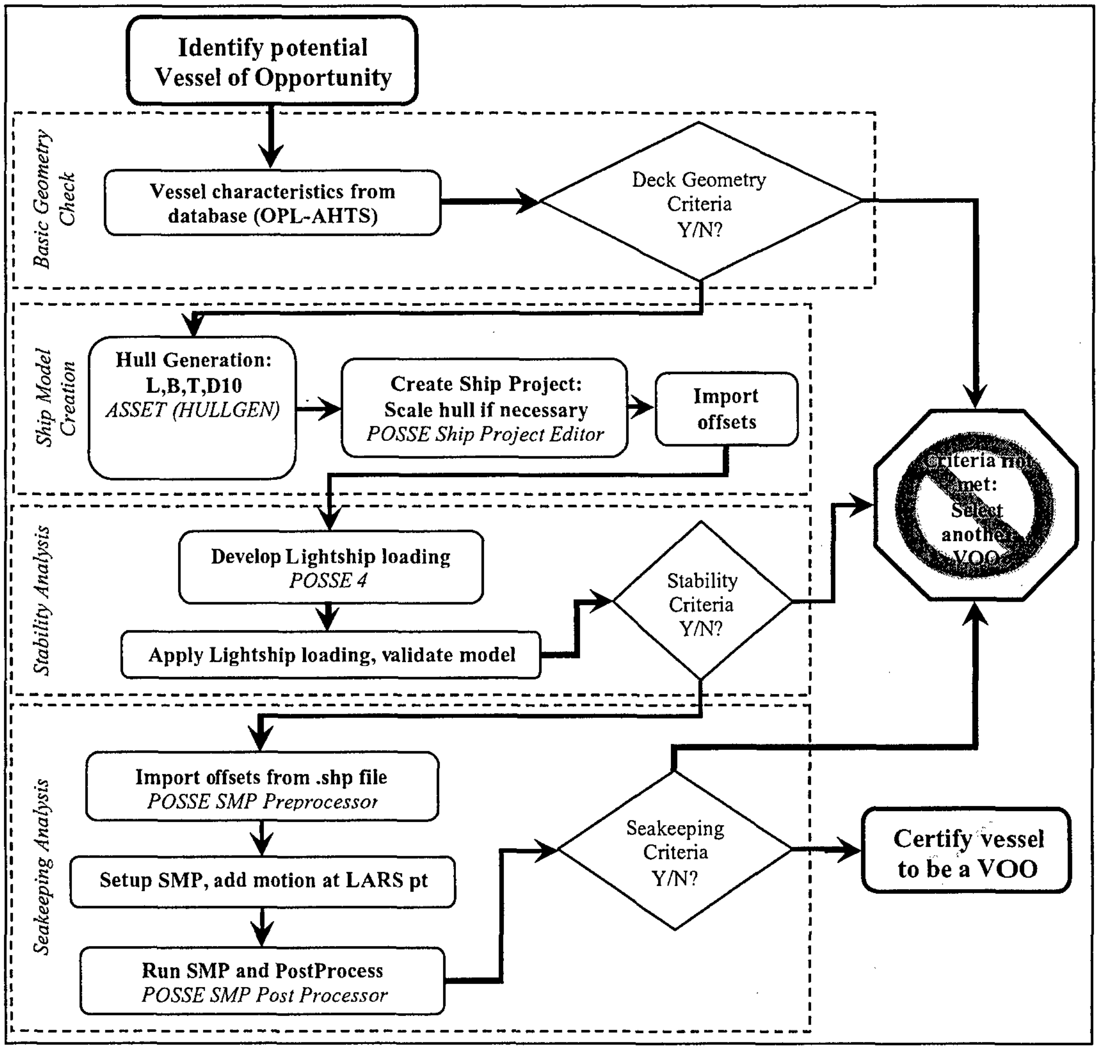

Figure 3.1. VOO Selection Procedure

3.1.1. Programs Utilized for Selection Procedure

The following are the databases and programs that are used for this procedure:

OPL-AHTS Database

The Oilfield Publications Limited (OPL), Anchor Handling Tugs and Supply Vessels of the World (AHTS) Database, is a Microsoft ACCESS database of Offshore Supply Vessels and anchor handling tugs. This database includes basic vessel characteristics and owner information. An example of an ACCESS query showing some of the information that is available in the database is shown in Figure 3.2. Although this database is not required in order to execute this procedure, it is one of the only complete sources for OSV and AHT vessels.

V001 : Select Query

VesselIndex	VESSEL_Name	LOA(m)	WIDTH(m)	DWT(t)	DECKLENGTH(m)	DECKWIDTH(m)	DECKSTRENGTH(t/m²)	DECKCARGO(t)
2887	Kerir 4	60.03	13.29	1901	30.5	10.5	5	500
2886	Kerir 3	60.03	13.29	1901	30.5	10.5	5	500
2084	Med Tre	60.2	13	1100	37	10.5	5	600
1241	Maridive 87	60.2	13	1200	36.4	10.8	5	650
2085	Asso Sei	60.2	13	1100	37	10.5	5	600
2144	Fratelli Neri	60.2	13	1220	36	10.5	5	500
2145	Augustea Quattro	60.2	13	1220	36	10.5	5	500
3180	Huahu	60.2	13	1083	31	11	5	625
1240	Maridive 86	60.2	13	1100	36.4	10.8	5	650
3181	A H Varazze	60.2	13		30	10	5	625
2987	Stanford Prince	60.22	12.19	1016	32	10.67	2.6	599
2686	Pacific Lion	60.28	12.81	1258	38.41	10.36	4	800
2865	Long Beach Tide	60.4	12.2	1114	33.54	9.76	2.6	780
1542	Dushane Tide	60.4	12.2	925	31.7	10.7	2.6	610
2266	Dea Champion	60.49	14	1040	35	10	5	350
2306	Dea Conquerer	60.49	14	1280	35	11	5	600
2300	Seacor Lenga	60.49	14		35	11	5	600
2079	Maridive 85	60.5	13	1200	37	10.97	5	800
2078	Capo Frasca	60.6	13.03	1116	37	10.5	5	800
2872	Zamil 09	60 61	13	1135	32.6	10.2	5	440
2873	Zamil 08	60.61	13	1135	32.6	10.2	5	550

Record: 5 of 633 (Filtered)

Figure 3.2. Example of AHTS Query filtered for potential VOOs

ASSET 5.0.0

The Advanced Surface Ship Evaluation Tool (ASSET) is a surface ship design and synthesis tool. This VOO selection procedure utilizes the Hull Geometry Module which is based on NAVSEA HULLGEN program. The Hull Geometry Module develops a set of hull offsets from basic ship characteristics such as LBP, beam, depth, prismatic coefficient, max section

coefficient. ASSET can also export the hull offsets as a ".shcp" file which can be modified, saved as an ".off" offsets file and imported into POSSE Ship Project Editor.

POSSE Ship Project Editor

The POSSE Ship Project editor is used to create the basic ship model that includes hull geometry, waterlines, and lightship weight. POSSE Ship Project Editor validates the ship model for the analyses that can be performed in POSSE 4.

POSSE 4

POSSE 4 is the Intact Loading and Salvage Response Module of the whole POSSE suite. Using the ship model developed in the Ship Project Editor, POSSE 4 can be used to develop different loading conditions by applying various liquid levels or weights at various points. The ship's stability can then be evaluated against either pre-determined stability criteria (i.e., U. S. Coast Guard or IMO) or user defined criteria. POSSE 4 is also used to export the ship hull and characteristics into POSSE SMP.

POSSE SMP

POSSE Ship Motions Program (SMP) utilizes hull geometry imported from the .shp file and user input draft and GZ data. Various sea spectra and sea state data can be utilized for the SMP analysis. SMP can also solve for motions at a point. The SMP Preprocessor assembles and verifies the validity of input data. After the SMP solver is run, the output data is read and displayed by the SMP Post Processor.

3.1.2. Required Information

Table 3.1 lists the minimum potential VOO information that is required to perform this analysis.

Table 3.1. Parameters Required for VOO Analysis

Parameter	
LOA	Length OverAll
B	Beam
T	Draft
D	Depth
DWT	Dead Weight Tonnage
The following are not required for stability or seakeeping analysis, but are required for an initial geometry check that the deck is capable of carrying the SRS	
Deck Length	
Deck Width	
Deck Cargo	
Deck Strength	

3.1.3. Criteria for Adequacy

The criteria against which the results of this procedure will be compared are listed in Table 1.2. The Deck Geometry criteria are based on the physical size requirements of the complete SRDRS installed on a VOO. The Stability criteria, IMO Resolution A.749(18)-3.1 (A.167), are used since they provide a good, general set of criteria. If desired, other criteria can be added or substituted within POSSE 4. The Seakeeping criteria are based on an initial seakeeping analysis performed on the T-ATF. Since the results of this seakeeping analysis were used for the design of the SRDRS including the LARS A-frame and associated deck templates (where the LARS is attached), these accelerations served as the limiting case.

3.2. Deck Geometry Verification

While this first step does not require any specific analysis, it does make a quick first check to make sure the ship has the requisite geometry for supporting the SRDRS.

3.3. Hull Offset Generation

The following procedure details the generation of the hull offsets from the ship's LOA, T, B, D within ASSET. This procedure uses ASSET's HULLGEN to create the vessel's offsets. The validity of those offsets can be checked by examining both graphical outputs (Figure 3.3) and the ASSET printed reports. Finally, the offsets are exported and modified so they can be imported into POSSE Ship Project Editor.

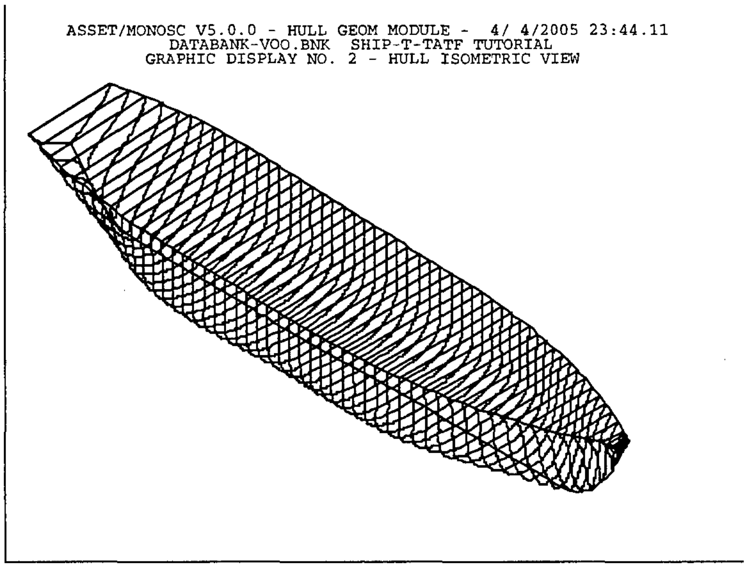

Figure 3.3. ASSET Hull Isometric View

3.4. Development of POSSE Ship Model

This part of the procedure creates the ship model in POSSE Ship Project Editor using hull offsets, draft and displacement data. The previously created hull offsets are imported into the editor and used to create the hydrostatic curves of form, Bonjean curves and cross-curves of stability. Since lightship weight distribution data are most likely not available, the procedure uses POSSE 4 to derive the lightship weight by entering the known deadweight and then iterating the lightship value and LCG position to achieve the reported draft on an even keel. The derived gross lightship weight is applied and distributed using an empirically based model that is part of the POSSE Ship Project Editor (Figure 3.4). Finally, the model is validated within the editor to ensure that the necessary stability analyses can be performed in POSSE 4.

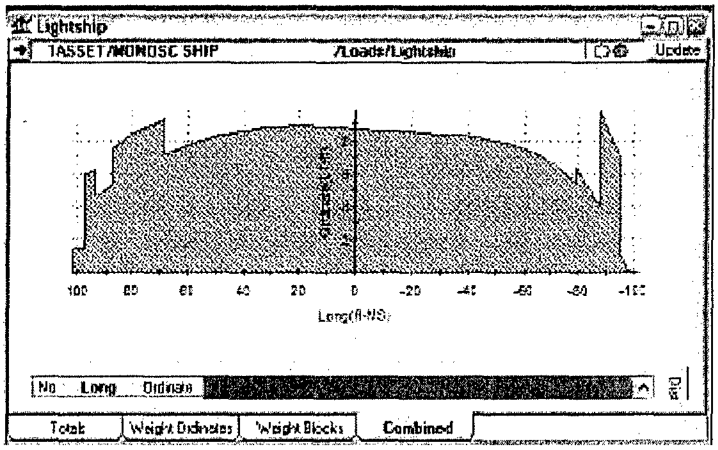

Figure 3.4. Lightship Weight Distributed

3.5. Stability Analysis in POSSE

The stability analysis is performed in POSSE 4 (Intact Loading and Salvage Response Module). The tutorial illustrates the analysis by applying three load plans: Lightship with SRS, Minimum Operating with SRS and Full Load with SRS. More can be defined if so desired. Based on load plans analyzed in "Trim and Stability Analysis" (Oceaneering International, Inc. 2003), the load plans recommended for the stability analysis are shown in Table 3.2. The relative weights, LCGs and VCGs are estimated from the T-ATF loading cases. Since these plans will be applied to different ships, the plans attempt to account for tankage as lumped weights that are a fraction of the dead weight tonnage. The plans assume that burned fuel will be compensated with, to a limited extent, seawater ballast (not necessarily in the same tanks or locations) and that the seawater tanks are near the baseline and serve to slightly lower the VCG due to the additional weight. Stability criteria (IMO A.749(18)-3.1 General Criteria) are applied from the beginning allowing stability to be assessed as POSSE continually updates calculations as each load plan is entered.

Table 3.2. Recommended Load Plans

Load Plan	Characteristic	Unit	Value
Departure with LARS Vertical	SRS	LT	183
	SRS LCG	ft AFP	41.24 ft fwd of the AP
	SRS VCG	ft ABL	8.69 + D20
	DISSB Crew	LT	0.00
	DISSB Crew LCG	ft AFP	0.00
	DISSB Crew VCG	ft ABL	0.00
	Addl (incl tanks)	LT	DWT × 0.7
	Addl LCG	ft AFP	MS
	Addl VCG	ft ABL	D20 × 0.45
Mid-Voyage with LARS vertical	SRS	LT	183
	SRS LCG	ft AFP	41.24 ft fwd of the AP
	SRS VCG	ft ABL	8.69 + D20
	DISSB Crew	LT	5.16
	DISSB Crew LCG	ft AFP	47 ft fwd of AP
	DISSB Crew VCG	ft ABL	D20 + 6
	Addl (incl tanks)	LT	DWT × 0.5
	Addl LCG	ft AFP	MS
	Addl VCG	ft ABL	D20 × 0.4
Return with LARS vertical	SRS	LT	183
	SRS LCG	ft AFP	41.24 ft fwd of the AP
	SRS VCG	ft ABL	8.69 + D20
	DISSB Crew	LT	5.16
	DISSB Crew LCG	ft AFP	47 ft fwd of AP
	DISSB Crew VCG	ft ABL	D20 + 6
	Addl (incl tanks)	LT	DWT × 0.3
	Addl LCG	ft AFP	MS
	Addl VCG	ft ABL	D20 × 0.3

3.6. Seakeeping Analysis in POSSE SMP

The seakeeping analysis using POSSE SMP utilizes the ship model created by the POSSE Ship Project Editor including the lightship weight distribution, and the GM data calculated by POSSE 4. All the hull, weight and stability data are entered into POSSE Preprocessor. At a minimum, the loading condition for the worst case of stability should be analyzed since that load case will also have the greatest response amplitude. After entering all the required sea state information and motions at a point for the desired location (LARS A-

Frame), the complete input data set is sent to SMP for analysis. Once SMP finishes its analysis, the output data is opened by the SMP Postprocessor.

SMP uses the lightship distribution to solve for the pitch and yaw radii of gyration during the SMP run. SMP estimates the roll radius of gyration to be 0.35 of the Beam. For the T-ATF, SMP estimates the roll radius of gyration to be 14.7 ft. It is actually 16.8 ft (DTCEL 2002, 5). This difference will lead to a higher roll response amplitude than the true response. But, this higher response is not as critical since the most important response to this analysis is the vertical acceleration at the LARS point which is due primarily to the pitch and heave responses.

After the SMP modules run, the results are sent to the SMP Post Processor. The Post Processor displays the full response data for examination (Figure 3.5). Each response direction can be examined for the motion point (LARS) for displacement, velocity, and, most importantly acceleration. The accelerations are then compared to the criteria for accelerations in order to judge adequacy.

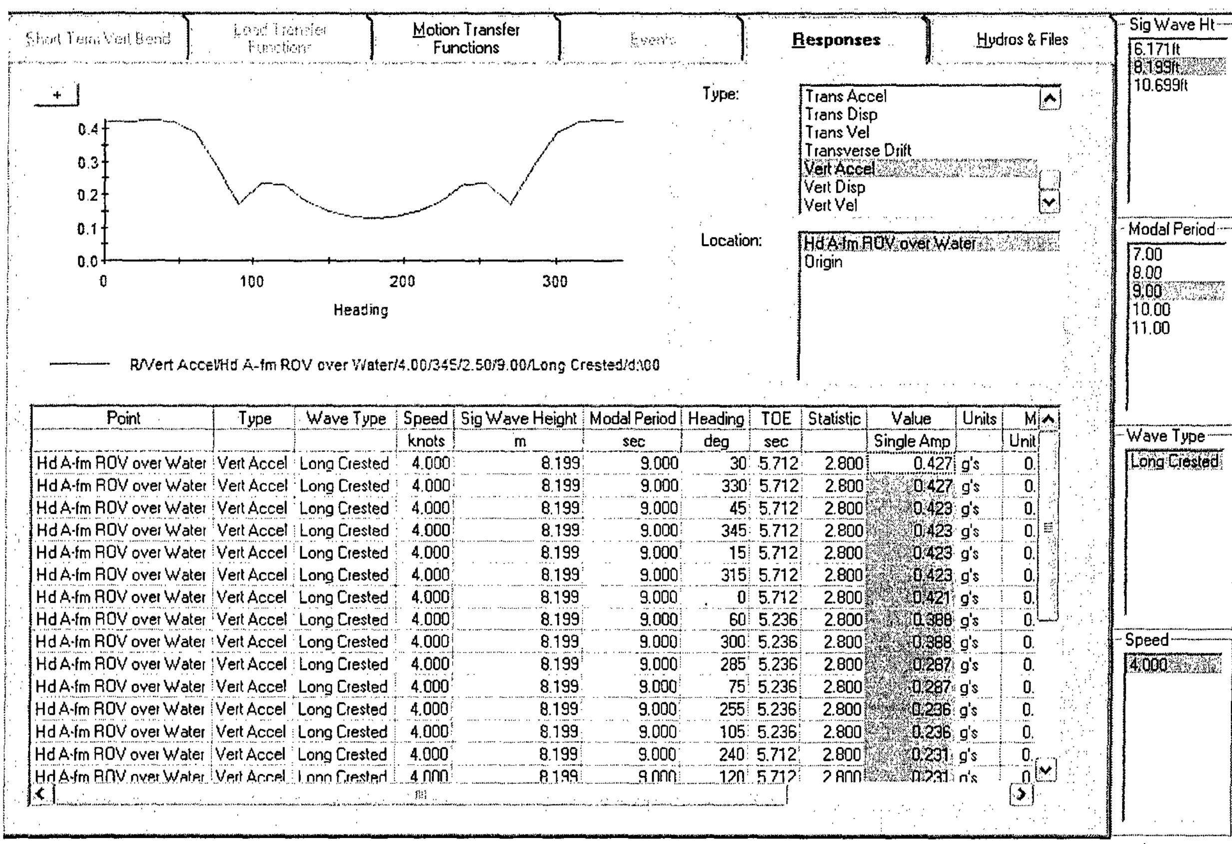

Figure 3.5. SMP Postprocessor Response Output

3.7. VOO Adequacy Analysis Procedure Conclusion

Execution of the procedure does require a basic knowledge of naval architecture and the programs being used. The first time through the procedure as a tutorial may take two to three hours. With familiarity, however, the time to fully analyze a potential VOO should be less than one hour. The criteria used in the tutorial are based on the documentation that was available for the SRDRS at the time this thesis was written. These adequacy criteria can and should be updated as the construction and testing are completed while still maintaining the underlying analysis procedures.

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Chapter 4. VERIFICATION OF VOO SELECTION PROCEDURE

4.1. Introduction

This chapter will test and demonstrate the validity of the VOO selection procedure, VAAP, detailed in Chapter 3 by using known results of stability and seakeeping analyses for the T-ATF that are part of the *SRS System Documents, Vessel of Opportunity Documents, Volume 9.* This chapter will also discuss the results of a sensitivity analysis that tested certain assumptions made for this procedure and examined the effect that varying the assumptions has on the final results of the analysis. Finally, this chapter will examine the results of applying this procedure to other example cases of potential VOOs.

4.2. Comparison of VOO Selection Procedure Results for the T-ATF versus Known Results

This comparison analysis will utilize limited vessel characteristics of the T-ATF as if this information came from the OPL-AHTS database. This information is listed in Table 4.1.

Table 4.1. Comparison Analysis T-ATF Vessel Information

	Units	T-ATF (Actual)	VOO TATF (Modeled)
LOA	ft	226	226
B	ft	42	42
DWT	LT	814	814
T	ft	15.5	15.5
D	ft	20	20

4.2.1. Hull Generation

This analysis started by generating the ship's hull offsets with ASSET HULLGEN using the data in Table 4.2. Depths at stations 0, 3, 10 and 20 were estimated based on the ship type, but this estimate will not change the results of the analysis from those of a constant station depth (which is what I used in the sensitivity analysis). C_P and C_X were estimated according to *PNA Vol. I* typical values for offshore supply vessels.

Table 4.2. Hull Generation Data

	Units	T-ATF (Actual)	VOO TATF (Modeled)	% Difference
LBP	ft	195	192.1	-1.49%
B	ft	42	42	0.00%
T	ft	15.5	15.5	0.00%
D0	ft	37	34	-8.11%
D3	ft	35	33	-5.71%
D10	ft	28.5	30	5.26%
D20	ft	20	20	0.00%
CP		0.716	0.729	1.82%
CX		0.893	0.906	1.46%
Main Dk ht	ft	28.5	30	5.26%

The hull generated in ASSET is shown in Figure 4.1. The "Hull Geometry Summary" is shown in Table 4.3.

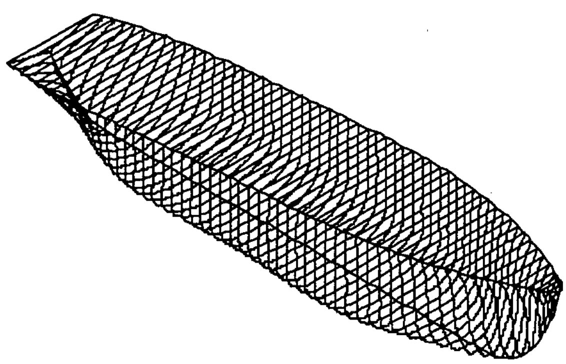

Figure 4.1. Comparison Analysis; T-ATF Hull Isometric View

Table 4.3. Comparison Analysis; Asset Hull Geometry Summary

```
      ASSET/MONOSC V5.0.0 - HULL GEOM MODULE -  4/14/2005 13:40.15
                       DATABANK-VOO.BNK  SHIP-COMP

 PRINTED REPORT NO.  1 - HULL GEOMETRY SUMMARY

 HULL OFFSETS IND-GENERATE            MIN BEAM, FT                 42.00
 HULL DIM IND-NONE                    MAX BEAM, FT                 42.00
 MARGIN LINE IND-CALC                 HULL FLARE ANGLE, DEG          .00
 HULL STA IND-OPTIMUM                 FORWARD BULWARK, FT           4.00
 HULL BC IND-GIVEN

                  HULL PRINCIPAL DIMENSIONS (ON DWL)
                  ==================================
 LBP, FT                     192.10   PRISMATIC COEF               0.729
 HULL LOA, FT                199.28   MAX SECTION COEF             0.906
 BEAM, FT                     42.00   WATERPLANE COEF              0.779
 BEAM @ WEATHER DECK, FT      42.16   LCB/LBP                      0.508
 DRAFT, FT                    15.50   HALF SIDING WIDTH, FT         1.00

 DEPTH STA 0, FT              34.00   BOT RAKE, FT                  0.00
 DEPTH STA 3, FT              34.00   RAISED DECK HT, FT            0.00
 DEPTH STA 10, FT             30.00   RAISED DECK FWD LIM, STA
 DEPTH STA 20, FT             20.00   RAISED DECK AFT LIM, STA
 FREEBOARD @ STA 3, FT        22.50   BARE HULL DISPL, LTON      2360.12

 STABILITY BEAM, FT           53.08   AREA BEAM, FT                19.21

       BARE HULL DATA ON LWL                STABILITY DATA ON LWL
       =====================                =====================
 LGTH ON WL, FT              192.08   KB, FT                        8.47
 BEAM, FT                     42.00   BMT,  FT                      9.29
 DRAFT, FT                    15.47   KG,  FT                      18.00
 FREEBOARD @ STA 3, FT        22.53   FREE SURF COR, FT             0.00
 PRISMATIC COEF               0.701   SERV LIFE KG ALW, FT          0.00
 MAX SECTION COEF             0.944
 WATERPLANE COEF              0.782   GMT, FT                      -0.25
 WATERPLANE AREA, FT2       6308.61   GML, FT                     149.32
 WETTED SURFACE, FT2        9976.70   GMT/B AVAIL                 -0.006
                                      GMT/B REQ                    0.100
 BARE HULL DISPL, LTON      2358.72
 APPENDAGE DISPL, LTON         7.92
 FULL LOAD WT, LTON         2366.63
```

4.2.2. Stability

For the stability portion of this comparison analysis, the ship model was created in POSSE, lightship weight distribution was developed and applied, and load case stability analysis was performed according to the procedure detailed in Section 3.5. Three load cases were specifically examined, all with the LARS in the vertical position (the worst possible VCG situation for the SRS load): Departure, Mid-Voyage and Return. The load cases used in this comparison are those originally estimated from the T-ATF load cases in "Trim and Stability Analysis" (Oceaneering International, Inc. 2003). To be consistent with the "Trim and Stability Analysis" that used an allowable VCG, the IMO General Stability Criteria required GM was subtracted from the KM in order to get an allowable VCG and judge adequacy for stability.

Although the estimations for load cases assume some compensation for burned fuel with seawater ballast, no other VCG compensation was applied. The results for the Departure, Mid-Voyage and Return load case stability analyses are summarized in Table 4.4,

Table 4.5, Table 4.6 and fully listed in APPENDIX B.

Table 4.4. Comparison Analysis; Departure LARS vert

	Units	T-ATF (Actual)	VAAP (Modeled)	% Difference
Displacement	LT	2096.43	2277	8.61%
LCG	ft AFP	102.93	99.59	-3.24%
VCG	ft ABL	18.18	17.51	-3.69%
SRS	LT	160.56	160.56	0.00%
SRS LCG	ft AFP	167.66	167.66	0.00%
SRS VCG	ft ABL	28.54	28.54	0.00%
DISSB Crew	LT	0.00	0	0.00%
DISSB Crew LCG	ft AFP	0.00	0	0.00%
DISSB Crew VCG	ft ABL	0.00	0	0.00%
Addl (incl tanks)	LT	379.89	570	50.04%
Addl LCG	ft AFP	121.05	96.05	-20.65%
Addl VCG	ft ABL	8.84	8	-9.46%
Max VCG	ft ABL	18.24	17.49	-4.11%
Actual VCG incl FSC	ft ABL	18.18	17.51	-3.69%
VCG Margin	ft	0.06	-0.02	-133.33%

Table 4.5. Comparison Analysis; Mid-Voyage LARS vert

	Units	T-ATF (Actual)	VAAP (Modeled)	% Difference
Displacement	LT	2062.94	2120	2.77%
LCG	ft AFP	102.58	100.02	-2.50%
VCG	ft ABL	18.15	17.99	-0.88%
SRS	LT	160.56	160.56	0.00%
SRS LCG	ft AFP	167.66	167.66	0.00%
SRS VCG	ft ABL	28.54	28.54	0.00%
DISSB Crew	LT	5.16	5.16	0.00%
DISSB Crew LCG	ft AFP	162.83	162.83	0.00%
DISSB Crew VCG	ft ABL	25.49	25.49	0.00%
Addl (incl tanks)	LT	341.40	407.00	19.21%
Addl LCG	ft AFP	117.99	96.05	-18.59%
Addl VCG	ft ABL	7.57	8.00	5.62%
Max VCG	ft ABL	18.42	17.63	-4.29%
Actual VCG incl FSC	ft ABL	18.15	17.99	-0.88%
VCG Margin	ft	0.27	-0.36	-233.33%

Table 4.6. Comparison Analysis; Return LARS vert

Return LARS vert				
	Units	T-ATF (Actual)	VAAP (Modeled)	% Difference
Displacement	LT	2026.26	2038	0.58%
LCG	ft AFP	101.33	100.17	-1.14%
VCG	ft ABL	18.35	18.07	-1.53%
SRS	LT	160.56	160.56	0.00%
SRS LCG	ft AFP	167.66	167.66	0.00%
SRS VCG	ft ABL	28.54	28.54	0.00%
DISSB Crew	LT	5.16	5.16	0.00%
DISSB Crew LCG	ft AFP	162.83	162.83	0.00%
DISSB Crew VCG	ft ABL	25.49	25.49	0.00%
Addl (incl tanks)	LT	304.83	326.00	6.94%
Addl LCG	ft AFP	113.90	96.05	-15.67%
Addl VCG	ft ABL	7.13	6.00	-15.90%
Max VCG	ft ABL	18.54	17.74	-4.31%
Actual VCG incl FSC	ft ABL	18.35	18.07	-1.53%
VCG Margin	ft	0.19	-0.33	-273.68%

This actual T-ATF stability with the low VCG margin shows that the T-ATF is a marginally stable case to support the SRS. The VAAP, while somewhat conservative (erring on

the side of low stability) also shows that the T-ATF is a marginal VOO. The modeled T-ATF is extremely sensitive to changes in VCG, and thus only marginally stable: the relatively low B/T ratio (~2.8) of the T-ATF compared to that of other offshore vessels that would be able to handle high VCG loads; and the fact that the payload SRS is a significant portion of DWT (20%) with a high VCG. The VAAP model of the T-ATF does have some significant differences in the inputs for lightship (resulting from the slightly fuller hull but same draft), load weights and VCGs. However, the results of the VOO Selection Procedure stability analysis, as measured by "Max VCG" and "Actual VCG", had differences never greater than 4.31% (not including VCG Margin which are higher mainly because of the difference in magnitudes from the VCGs to the VCG Margin) and were always more conservative than the actual stability as measured by VCG margin.

4.2.3. Seakeeping

As with the stability comparison analysis, the seakeeping comparison analysis sought to evaluate the validity of the VAAP applied to the T-ATF against known results. In this case, the VAAP T-ATF model was compared against the John J. McMullen Associates (JJMA) "Motions and Dynamic Load Factors for Sub Rescue Vehicle Handling System Aboard T-ATF" and David Tein Consulting Engineers, Ltd. (DTCEL) "Navy T-ATF Vessel Motion Analysis Report." The JJMA seakeeping analysis used SMP. The DTCEL seakeeping analysis used the computer program AQWA from Century Dynamics. AQWA performs three dimensional motion analysis using "diffraction theory and Morison's equation" (DTCEL 2002, 6). Table 4.7 lists the basic vessel characteristics of each respective model. The last two columns are the percent differences of the VAAP T-ATF model from the JJMA T-ATF model and the DTCEL T-ATF model.

Table 4.7. Comparison Analysis; Seakeeping Models

Model:	Units	JJMA	DTCEL	VAAP T-ATF	%Diff from JJMA	%Diff from DTCEL
T	ft	14.96	14.05	14.97	0.07%	6.55%
Disp	LT	2240	2035	2277	1.65%	11.89%
LCG	ft AFP	101.37	102.35	99.59	-1.76%	-2.70%
VCG	ft ABL	17.1	18.12	17.51	2.40%	-3.37%

The results of the POSSE SMP simulation and the comparison to the JJMA and DTCEL analyses are listed in full in Appendix A and summarized in Table 4.8 and Table 4.9. The VAAP T-ATF model was based on the POSSE lightship weight distribution as well as the SRS, DISABLED SUBMARINE Personnel and Addition Load. Because that weight distribution is only in the longitudinal direction, SMP calculates the radii of gyration for pitch and yaw and uses a default estimate for the roll radii of gyration: $K_{roll}=0.35 \times B$. This helps explain the rather large difference in ship response about the roll axis direction for the VAAP as well as the large difference in transverse acceleration from the other analyses.

Table 4.8. Comparison Analysis; Ship Motion Seakeeping Results at CG

Ship Motion	Units	JJMA	DTCEL	VAAP T-ATF	%Diff from JJMA	%Diff from DTCEL
Sig Wave Ht	ft	8.2	8.2	8.199	-0.01%	-0.01%
Wave Pk Per	s	9	9	9	0.00%	0.00%
Max Roll Accel	deg/s^2	6.6	4.195	1.981	-69.98%	-52.78%
Resp Per	S	10	7.513	5.712	-42.88%	-23.97%
Max Pitch Accel	deg/s^2	4.79	5.098	4.107	-14.26%	-19.44%
Resp Per	S	7	5.128	5.712	-18.40%	11.39%

For the case of vertical acceleration, the VAAP comes much closer to matching both the JJMA and DTCEL analyses. The slightly lower acceleration response here may be due to the slightly fuller hull form than the actual T-ATF that was developed as part of this procedure. The impact of the coefficients are explored in more detail in the sensitivity analysis, Section 4.3.2. below. Of all the responses, though, the vertical acceleration is the most important since that acceleration most directly impacts loading of the LARS foundation attachment to the deck.

Table 4.9. Comparison Analysis; Seakeeping Results at Head of LARS with ROV Over Water

	Units	JJMA	DTCEL	VAAP T-ATF	%Diff from JJMA	%Diff from DTCEL
Max Trans Accel	ft/s^2	0.151	0.215	0.286	89.40%	33.02%
Resp Per	S	8	5.817	5.236	-34.55%	-9.99%
Max Vert Accel	ft/s^2	0.31	0.346	0.298	-3.87%	-13.87%
Resp Per	S	7	5.221	5.236	-25.20%	0.29%

4.3. Sensitivity Analysis of Assumptions

This sensitivity analysis is intended to explore the gross effects of varying the coefficients and variables that were used in developing the input model for the VAAP: C_B, C_X, lightship VCG, and lightship LCG. In order to explore a reasonable variable space without examining every point, the design of experiments program JMP was used to develop the "experiment." *PNA Vol. I* (SNAME 1988, vol. 1; 20) served as a guide for developing a typical range of values for each of the input variables. Table 4.10 lists the range for each coefficient or variable with VCG and LCG nondimentionalized.

Table 4.10. Sensitivity Analysis Input Variable Ranges

Input Variables	low	typical	high
Cp	0.6	0.729	0.8
Cx (Cm)	0.83	0.906	0.98
VCG/D10	0.8	0.84	0.96
LCG/L	0.55	0.5	0.45

With the range of each variable set, JMP was used to develop the run pattern for a Central Composite Design, four factor, 25 run experiment. This setup would help explore the boundaries of the variable space in order to uncover any trends or excessive sensitivity the VAAP may have to one or any combination of the input variables. The random run pattern JMP developed is shown in the left-hand side of Table 4.11 with three values for each variable, where "1" is the highest value, "0" is the "typical" value, and "-1" is the lowest value for each of the X1, X2, X3

and X4 variables. The right-hand portion of this table shows each run translated into the respective coefficient value. These values serve as the input for 25 successive runs of the VAAP. Every other part of the VAAP, this sensitivity analysis used the T-ATF characteristics and followed the procedure detailed in Chapter 3 with only one load case consisting of the SRS (183 LT) and an Additional Load (163 LT).

Table 4.11. JMP Run Pattern

Run	X1	X2	X3	X4		Cp (X1)	Cx (X2)	VCG/D10 (X3)	LCG/L (X4)
1	0	1	0	0		0.729	0.98	0.84	0.5
2	1	-1	1	1		0.8	0.83	0.96	0.45
3	0	0	1	0		0.729	0.906	0.96	0.5
4	-1	-1	1	1		0.6	0.83	0.96	0.45
5	1	1	1	1		0.8	0.98	0.96	0.45
6	1	1	-1	1		0.8	0.98	0.8	0.45
7	1	-1	1	-1		0.8	0.83	0.96	0.55
8	-1	1	1	1		0.6	0.98	0.96	0.45
9	0	0	0	-1		0.729	0.906	0.84	0.55
10	0	0	-1	0		0.729	0.906	0.8	0.5
11	-1	-1	-1	-1		0.6	0.83	0.8	0.55
12	1	-1	-1	-1		0.8	0.83	0.8	0.55
13	1	0	0	0		0.8	0.906	0.84	0.5
14	0	0	0	0		0.729	0.906	0.84	0.5
15	-1	1	1	-1		0.6	0.98	0.96	0.55
16	-1	0	0	0		0.6	0.906	0.84	0.5
17	-1	-1	1	-1		0.6	0.83	0.96	0.55
18	0	-1	0	0		0.729	0.83	0.84	0.5
19	-1	-1	-1	1		0.6	0.83	0.8	0.45
20	-1	1	-1	-1		0.6	0.98	0.8	0.55
21	0	0	0	1		0.729	0.906	0.84	0.45
22	1	1	-1	-1		0.8	0.98	0.8	0.55
23	-1	1	-1	1		0.6	0.98	0.8	0.45
24	1	-1	-1	1		0.8	0.83	0.8	0.45
25	1	1	1	-1		0.8	0.98	0.96	0.55

4.3.1. Stability Sensitivity Analysis

The full results of the stability portion of the sensitivity analysis are in Appendix B. These results are summarized parametrically for initial GM_T in Figure 4.2 (GMt in the figure) and max GZ in Figure 4.3 for varying VCGs (the two boundary values) at each combination of C_X and C_P. The straight lines connecting the two respective combinations of C_X and C_P do not necessarily indicate a linear relationship.

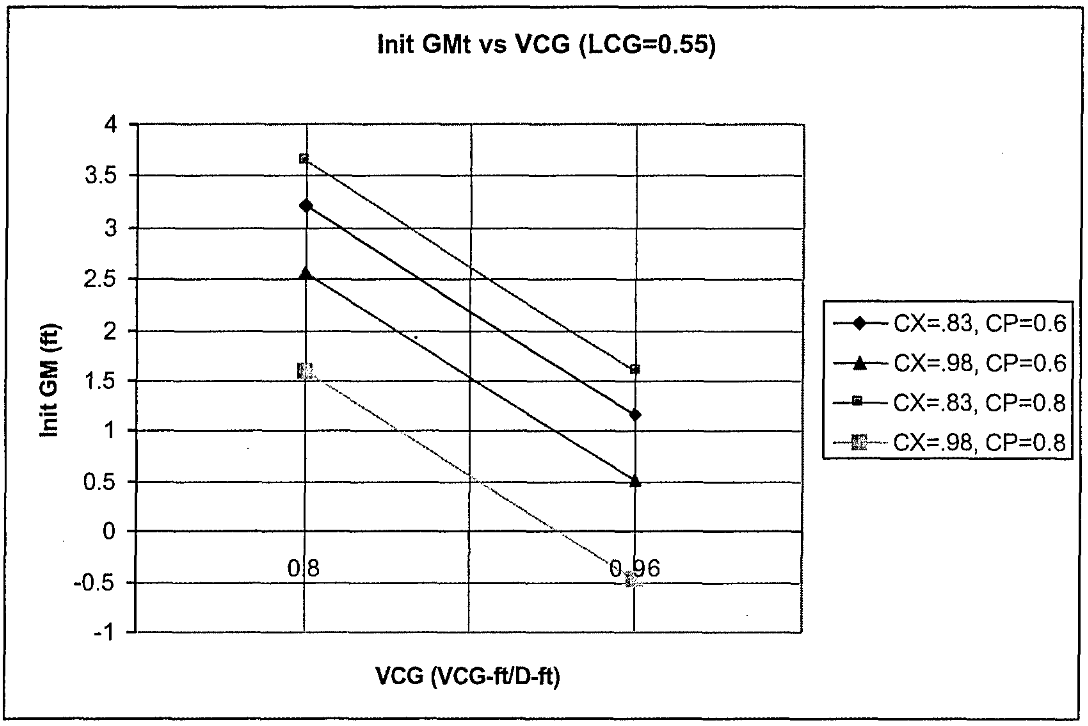

Figure 4.2. Initial GMt vs VCG

The results for initial GM_T (Figure 4.2) demonstrate the expected dependence of stability on VCG. While it is interesting to note that GM_T is reduced as C_P increases, the same is not true for C_X. Most importantly, though, is the exaggerated effect that the combination of a high C_X and a high C_P has on reducing GM_T.

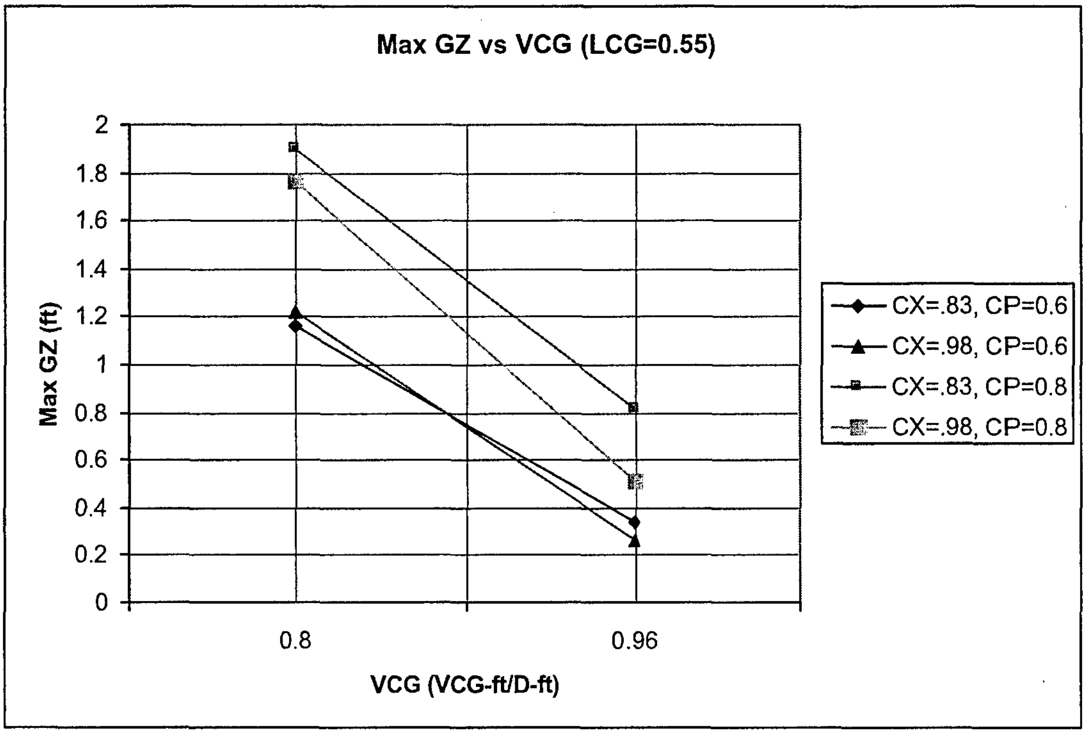

Figure 4.3. Max GZ vs VCG

The results for max GZ (Figure 4.3) again show the dependence of stability on the height of VCG. But here, because max GZ is the righting arm at the maximum roll position (40 deg), the fuller hull shape (higher C_P) results in a higher righting arm and varying C_X has a less pronounced effect.

4.3.2. Seakeeping Sensitivity Analysis

As with the stability sensitivity analysis, the seakeeping sensitivity analysis was intended to examine the effect of the same four variables and used the process and assumptions of the VAAP with the following exception. Both runs 5 (C_P +, C_X +, VCG/D10 +, LCG/L +) and 25 (C_P +, C_X +, VCG/D10 +, LCG/L -) had negative initial GM. Because SMP cannot evaluate the ship motions for an unstable case, the Additional Load VCG was slightly lowered and the LCG moved slightly forward to achieve marginally positive stability (this is only for application to SMP). While making this modification does somewhat taint the results for those specific runs, the goal of this sensitivity analysis is to uncover trends, not to obtain specific numerical results.

As with VAAP, load distribution (lightship and additional loads) were imported from POSSSE into SMP for each load case. For consistency and to exaggerate the effect on ship motions that a variable, or combination of variables has, each SMP run was performed at SS5: Bretschneider Spectrum, 13.123 ft significant wave height and 9.7 s wave period. All the responses in this sensitivity analysis are for the head of the LARS frame with PRM over water since this is the most critical case for loading of the LARS base. The full seakeeping response results are listed in Appendix B.

As shown in Figure 4.4, the response of max vertical acceleration shows very little dependence on C_X, C_P or VCG. This is to be expected since the primary component of the vertical motions at this point are due to the pitch response which are, in turn, dependent mostly on the length of the ship and the gross longitudinal weight distribution. Figure 4.5 also shows the independence of Max Vertical Acceleration to C_X, C_P or LCG where the LCG variation was 10%.

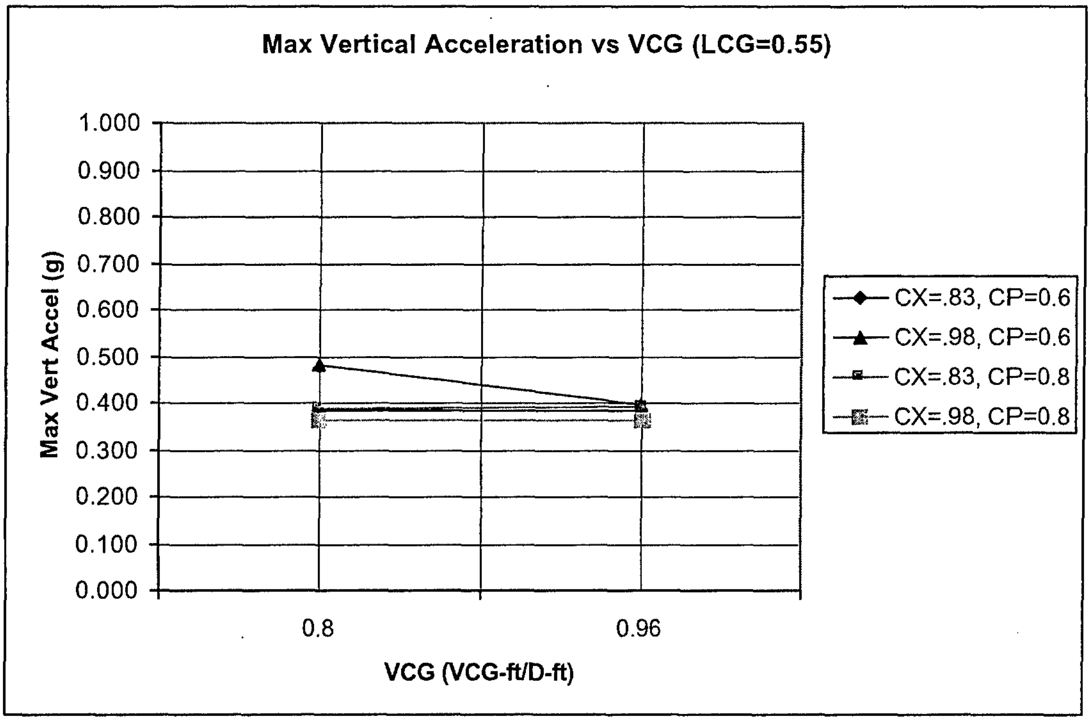

Figure 4.4. Max Vertical Acceleration vs VCG

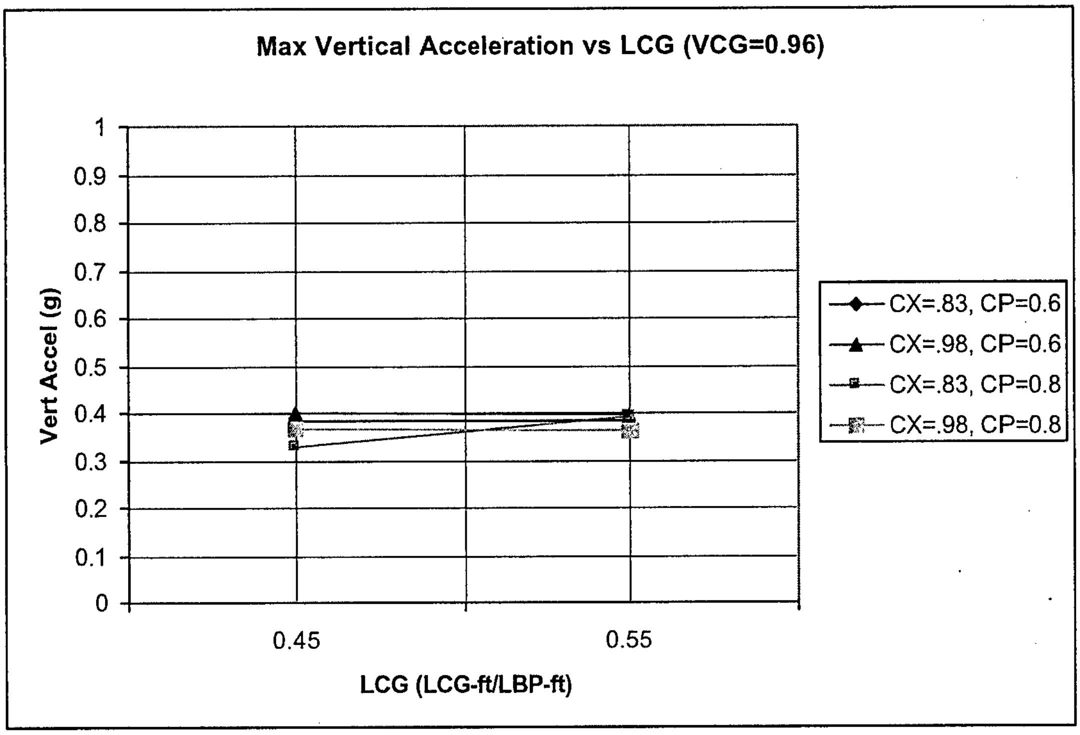

Figure 4.5. Max Vertical Acceleration vs LCG

The response for the transverse acceleration is not entirely accurate since it is primarily a result of the ship's roll response for which SMP uses the default radius of roll gyration (0.35 of the Beam). Nonetheless, Figure 4.6 and Figure 4.7 illustrate two interesting results. First, in the vicinity of the VCG/D of approximately 0.93, there is little variation in the transverse acceleration across the values of C_X, C_P. The second interesting result involves the trend of transverse acceleration for increasing VCG. Specifically, a full hull (high C_X and high C_P) results in a lower transverse acceleration at the low VCG than the less full hull (low C_X and low C_P). The same full hull has higher transverse acceleration with the higher VCG.

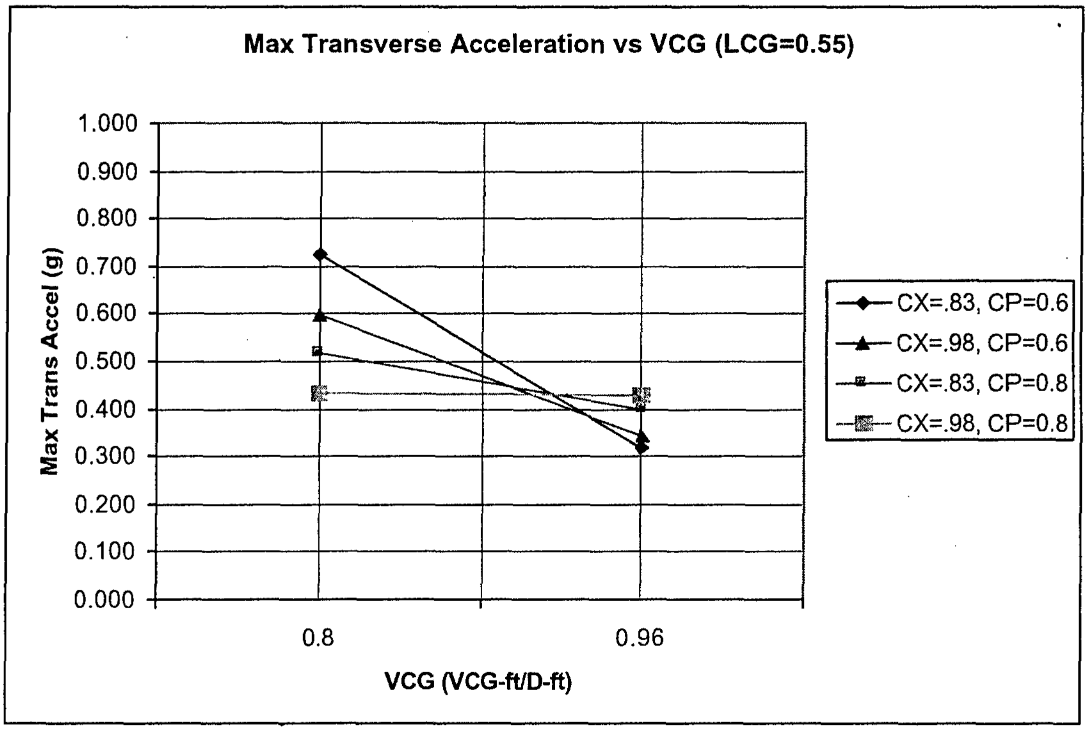

Figure 4.6. Max Transverse Acceleration vs VCG

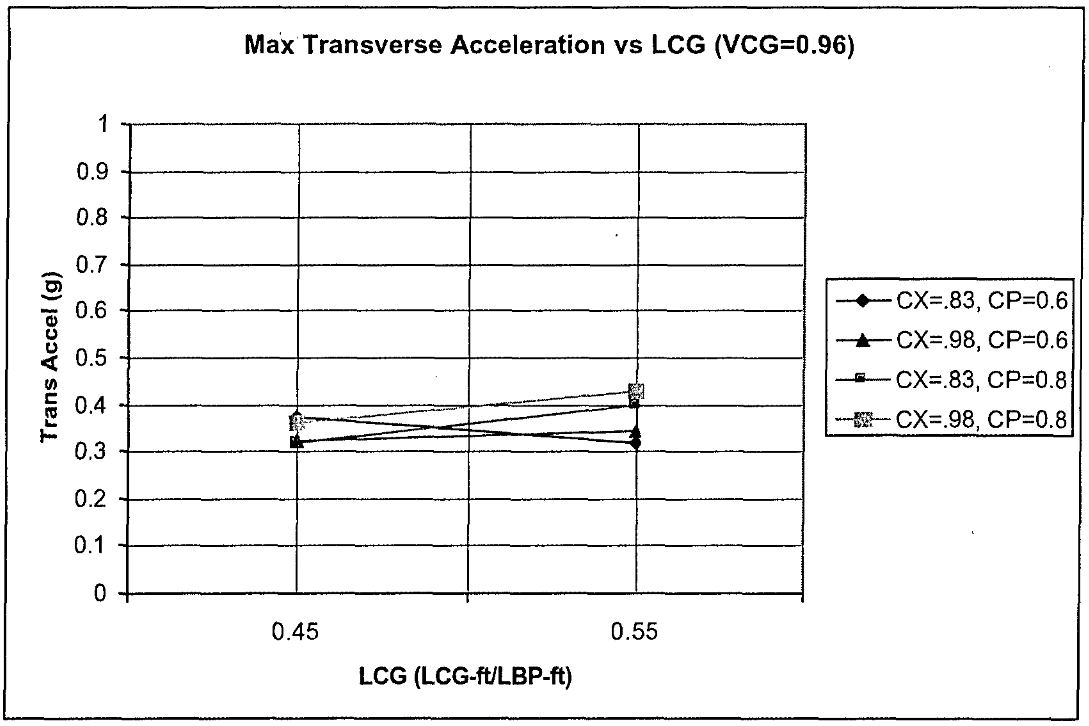

Figure 4.7. Max Transverse Acceleration vs LCG

4.3.3. Sensitivity Analysis Conclusion

The sensitivity analysis illustrated the effects of varying the more significant of the variables that are assumed for the VOO analysis. Because the VOO analysis involves the interaction of multiple variables, the trends which this sensitivity analysis uncovered can assist those actually conducting the analysis if changes to the default variables are desired. This sensitivity analysis also demonstrated that a conservative and relatively accurate stability and seakeeping analysis can be conducted for this type of vessel using the PNA typical values.

4.4. Results and Observations for Other Potential VOOs: OSV, AHTs and Barges

This section illustrates two example applications of the VAAP to other possible VOOs: an anchor handling tug picked at random from the OPL-AHTS database, and an ocean going deck barge.

4.4.1. Anchor Handling Tug Example Analysis

The "Neftegaz-51" was arbitrarily selected from the OPL-AHTS database after applying a filter in Access for the required deck geometry, scrolling down through the available vessels (633 total) and selecting this vessel at random (Figure 4.8).

VOO2 : Select Query

VesselIndex	VESSEL_Name	LOA(m)	WIDTH(m)	DWT(t)	DECKLENGTH(m)	DECKWIDTH(m)	DECKSTRENGTH(t/m²)	DEC
408	Nan Hai 210	64.7	13.8	1841.4	37.8	11	5	
409	Nan Hai 211	64.7	13.8	1841.4	37.8	11	5	
2467	Nan Hai 212	66.5	12.1	1775	33.5	11	5	
3062	Nan Hai 213	67.87	14.5	1190	35	11	5	
2382	Nan Hai 215	67.84	15.6	2209	37	12.8	5	
1214	Nan Hai 216	68.02	14.5	1968	38	11	5	
1756	Nan Ou	66.3	14.2	1260	30	11.5	5	
1755	Nan Ying	66.3	14.2	1260	30	11.5	5	
929	Nautical Tide	74.5	17.8	2276	30	16.8	2.5	
2978	Navis King	63.38	12.81		33.5	11	5	
1841	Neftegaz- 9	81.39	16.3	1396	38.75	11.35	5	
1855	Neftegaz-30	81.16	16.3	1382	38.75	11.35	5	
2908	Neftegaz-31	81.37	16.3	1382	36.3	11.35	5	
2507	Neftegaz-51	81.37	16.3	1350	38.75	11.35	5	
2745	Noordhoek Singapore	65.5	14.05	2124	39	11	5	
2122	Nordertor	61.9	13	1165	28.6	10	3	
564	Normand Atlantic	80.4	18	4200	36.5	15.5	10	
1056	Normand Borg	80	18	2750	37	15.35	5	
548	Normand Carrier	84.38	18.8	4560	59	16.2	5	
391	Normand Draupne	83.45	18	2500	42	15.5	10	

Record: 374 of 633 (Filtered)

Figure 4.8. Random Selection of a Potential VOO

The vessel information from the OPL-AHTS database used for the procedure is listed in Table 4.12.

Table 4.12. Neftegaz-51, Anchor Handling Tug Characteristics

STARTING INFO		Database #2507		
Characteristic	units	Neftegaz-51	units	Converted
LOA	m	81.37	ft	266.962
B	m	16.3	ft	53.47769
DWT	mt	1350	LT	1328.679
T	m	4.91	ft	16.10892
D	m	7.2	ft	23.62205
Deck Length	m	38.75	ft	127.1326
Deck Width	m	11.35	ft	37.23753
Deck Strength	t/m²	5	LT/ft²	0.471965
Deck Cargo	mt	700	LT	688.9449

Following the VAAP, the hull geometry was created in ASSET, followed by creating the ship model in POSSE, and developing and applying the lightship weight distribution. The stability analysis was performed for all three of the recommended loading cases and the seakeeping analysis was performed for the loading condition which had the worst stability (full results are listed in APPENDIX D). The worst case loading condition results for both the

stability and seakeeping analyses are shown in Table 4.13. Based on this analysis, the Neftegaz-51 would make an adequate VOO. Not only is the size of the Neftegaz-51 much larger than the T-ATF in L, B and displacement, but more importantly for stability, the B/T ratio (3.31) is much larger than that of the T-ATF (2.71).

Table 4.13. Worst Case Stability Loading Case: Return with LARS Vertical

Return LARS vert			Reqired
Displacement	LT	3277.00	
LCG	ft AFP	121.69	
VCG	ft ABL	21.61	
SRS	LT	183.00	
SRS LCG	ft AFP	214.76	
SRS VCG	ft ABL	32.31	
DISSB Crew	LT	5.16	
DISSB Crew LCG	ft AFP	162.83	
DISSB Crew VCG	ft ABL	25.49	
Addl (incl tanks)	LT	398.60	
Addl LCG	ft AFP	128.00	
Addl VCG	ft ABL	7.09	
Area to 40 deg	ft-deg	59.54	>16.92
Max GZ	ft	2.79	>0.66
Initial GM	ft	3.86	>0.49
LARS Long Accel	g	0.052	<0.2
LARS Trans Accel	g	0.313	<0.39
LARS Vert Accel	g	0.264	<0.31

4.4.2. Ocean Going Barge Example Analysis

The McDonough Marine 200 ft ocean going barge was also arbitrarily picked for analysis using the VOO analysis procedure for atypical VOOs (non-OSVs or AHTs). As with vessel characteristics from the OPL-AHTS database, the information found online for this barge was minimal (McDonough Marine 2005). Table 4.14 lists the full characteristics for this barge.

Table 4.14. Ocean Going Barge Characteristics

STARTING INFO		Ocean Going Barge McDonough Marine
Characteristic	units	(200 ft x 50 ft x 13 ft barge)
LOA	ft	200
B	ft	50
DWT	LT	1460
T	ft	7
D	ft	13
Deck Length	ft	200
Deck Width	ft	50
Deck Strength	LT/ft^2	N/A
Deck Cargo	LT	2600

The hull geometry for the barge was entered directly into POSSE as offsets ignoring any rake geometry since that was unknown. Table 4.15 lists the data used to generate the barge hull as shown in Figure 4.9.

Table 4.15. Ocean Going Barge Hull Generation Data

Hull Generation Info		
LBP	ft	200.00
B	ft	50.00
T	ft	7.00
D0	ft	13.00
D3	ft	13.00
D10	ft	13.00
D20	ft	13.00
CP		1.00
CX		1.00
Main Dk ht	ft	13.00

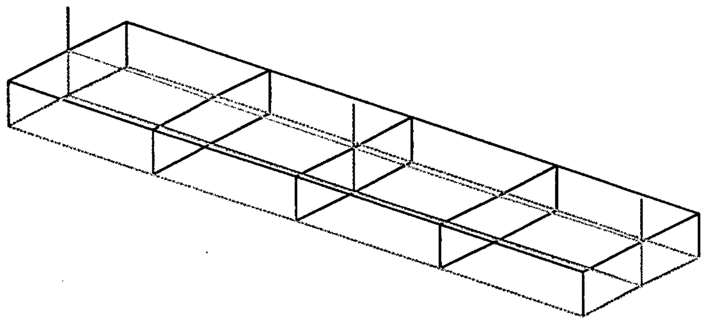

Figure 4.9. Barge Hull Geometry

The procedure progressed as it would for a regular VOO with the exception of the applied load. Since this barge would not have any appreciable fuel load for propulsion, the various loading conditions were not necessary. Instead, the barge was assumed to have at least limited ballast tankage to achieve an even heel and trim and compensate for bringing on personnel from the disabled submarine. Table 4.16 shows the results for both the stability and seakeeping analyses. As would be expected of a barge, the stability was excellent. However, the seakeeping analysis found that the transverse accelerations were in excess of the required accelerations (0.39g). This is likely due to the low radius of roll gyration that POSSE SMP assumes. And, since this response is for headings off the beam, operational constraints (always heading into the prevailing seas for recovery operations) could prevent this large acceleration.

Table 4.16. Barge Worst Case Stability Loading Case with LARS Vertical

Mid-Voyage LARS vert			Req'd
Displacement	LT	1133.00	
LCG	ft AFP	100.95	
VCG	ft ABL	8.48	
SRS	LT	183.00	
SRS LCG	ft AFP	158.76	
SRS VCG	ft ABL	21.69	
DISSB Crew	LT	5.16	
DISSB Crew LCG	ft AFP	162.83	
DISSB Crew VCG	ft ABL	18.49	
Addl (incl tanks)	LT	400.00	
Addl LCG	ft AFP	100.00	
Addl VCG	ft ABL	5.20	
Area to 40 deg	ft-deg	378.86	>16.92
Max GZ	ft	12.15	>0.66
Initial GM	ft	46.31	>0.49
LARS Long Accel	g	0.046	<0.2
LARS Trans Accel	g	0.498	<0.39
LARS Vert Accel	g	0.217	<0.31

4.5. Conclusion

The comparison analysis illustrates that while the proposed procedure makes assumptions that may lead to a model that is slightly different than the actual vessel, the final results are acceptably close (and more conservative) to other analyses that use more detailed information. The sensitivity analysis further demonstrated the effect that varying the input parameters had on the outcome of the procedure. The results of both help to demonstrate the validity of the procedure as well as provide guidance for how the assumptions used in the procedure could be modified in the future to make results more accurate.

Chapter 5. ANALYSIS OF OPTIONS FOR IMPLEMENTATION OF VOO SELECTION

5.1. VOO Selection in Practice

While Navy personnel will command rescue missions and provide divers, operators and medical support, most of the administration, maintenance, logistics coordination and technical support will be provided by a contractor. Part of the contractor responsibilities is the rapid execution of the VOO selection process and coordination of securing a charter for the selected VOO. The VOO adequacy analysis procedure which this thesis proposes is intended to be used on an as needed basis to evaluate potential VOOs in case of an SRDRS response to a disabled submarine. However, other options exist which could extend the capability of this procedure in either accuracy or speed of execution with the goal of improving the overall VOO selection process. The options for extending the use of this procedure or in some way pre-qualifying potential VOOs include:

- Establishing and maintaining a database of pre-qualified VOOs.
- Establish a special VOO classing with major classification societies (ABS, DNV, Lloyd's, etc).
- Encourage potential VOO builders and owners to construct their new vessels to the requirements of the SRDRS or verify that their design meets these requirements.

5.2. VOO Selection Process

The VOO selection process that will be executed by the managing SRDRS contractor is summarized in Figure 5.1. Upon notification of a disabled submarine and the location of the submarine, the contractor will begin gathering and identifying all relevant information required for operational deployment. This information includes location and nearest port information as well as situational deployment requirements based on the specific nature of the incident (some parts of the SRDRS may not be required for certain situations). Ship brokers are also contacted at this point to identify the locations of potential VOOs and prepare for acquiring a charter for

the necessary VOOs. Next, the personnel, system components, and other assets that are required for the mission are identified and prepared for deployment. The potential VOOs that were earlier identified are now analyzed for their adequacy to meet the VOO requirements. Once these vessels are down-selected for adequacy, they are further evaluated for which vessel is closest to the operating location and best port for the arriving SRDRS. Both the seaport facilities and the vicinity of an airport are of concern. Once the adequate VOO(s) are selected, the ship brokers are again contacted and the process of chartering the desired vessels is started. At this time, the port of embarkation is also probably known which would allow for full deployment of SRDRS personnel and equipment.

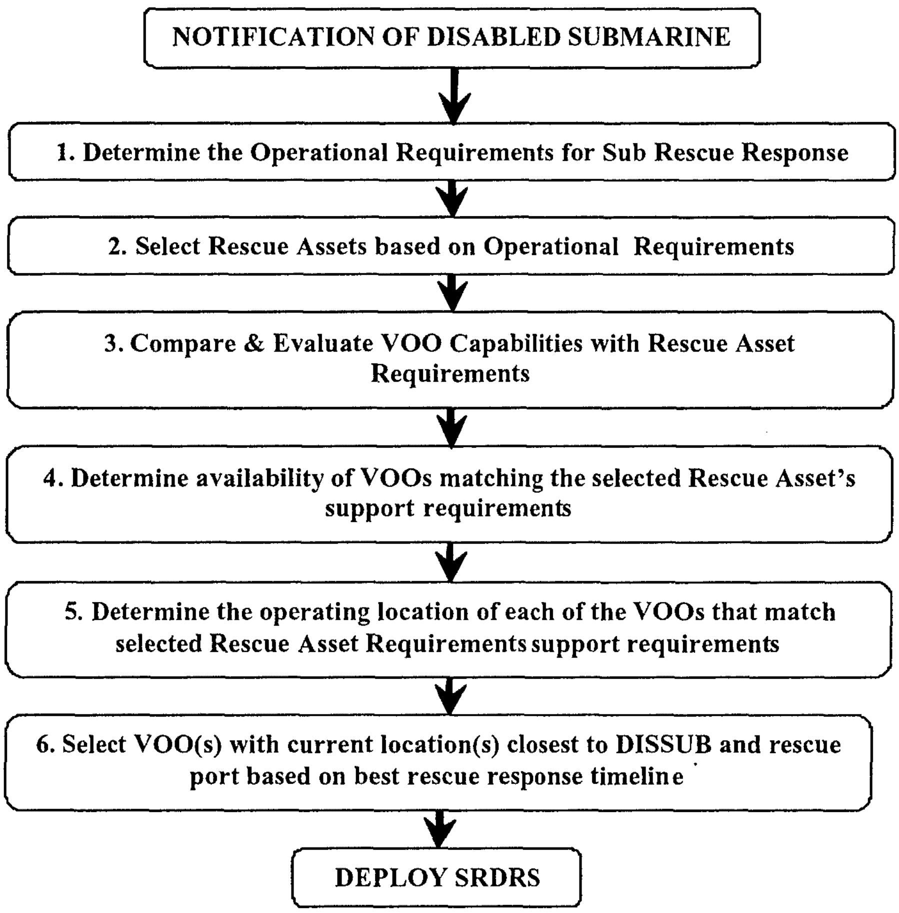

Figure 5.1. VOO Operational Selection Process (NAVSEA 2004, 3)

5.3. VOO Selection Process Improvement Options

The goal of improving the VOO selection process is to minimize the time it takes to deploy the system. Although there are many external variables which will affect this process including interactions with the ship brokers, availability of information, and the availability of vessels, the impact of these unknowns can be reduced if the time spent internally by the contractor analyzing and selecting the VOO is minimized. No matter how the process is improved, one factor will be absolutely necessary: an established relationship with shipbrokers worldwide who understand the requirements of the VOO. The vessel may be selected and the whole deployment plan may be in place, but that plan cannot proceed without the ship broker establishing a charter and coordinating with the vessel owner and operator.

5.3.1. Establish Pre-qualified VOO database

This option would create a database of all potential VOOs and analyze each based on the procedure proposed in this thesis as well as other structural adequacy analyses. Creating this sort of database could extend to gathering more detailed information for improving the accuracy of the analyses. This additional information could include hull offsets, load plans and weight reports, engineering drawings, structural information and vessel inspection reports.

Some of the information for potential VOOs, especially offshore barges, may be difficult to acquire before an actual incident. But, a database of qualified VOOs should attempt to have as complete knowledge as possible about the VOO pool of vessels. This database would require the SRDRS contractor to have personnel dedicated to maintaining this database as well as engineers and analysts collecting information and populating the database. Establishing this database could surely start with the OPL-AHTS database, but it would have to expand to include newly constructed vessels, especially barges and other atypical VOOs (non-OSV or AHT vessels). Gathering information about the atypical VOOs would be especially important in locations without offshore industry where OSVs and AHTs do not normally operate. A close relationship with ship brokers could aid in information gathering as well as locating and tracking vessels. The development of this database would be quite labor intensive, requiring the contractor to create and update the database as each new potential VOO is identified, analyzed and qualified. The long term maintenance of the database would be somewhat less labor

intensive, but newly constructed vessels would still have to be analyzed so they could be added to the database.

The more vessels that are approved and in the database, the quicker the deployment process can proceed. Once the ship broker is contacted to identify the potential VOOs, the database could be checked in real time against the available vessels. Additional location information could be linked to the vessel information allowing vessels that are qualified VOOs and are in the best location to be selected, enabling the process to proceed as rapidly as possible.

5.3.2. VOO Classing

Another option that could be a standalone criteria for a VOO or, what is more likely, augment other options, is the establishment of a special VOO classing with any or all major classification societies such as: ABS, DNV, Lloyd's Register, etc. Such a classification would require a newly constructed vessel to be designed, constructed and surveyed to rules based on the requirements necessary to support the SRDRS. Existing vessels could also be re-classed to support the SRDRS if they meet the requirements. While the information on which vessels have been classed to support the SRDRS could be contained in a standalone database, it could also augment the database option discussed in the previous section.

Another possibility would be to combine the requirements of the SRDRS with the NATO Submarine Rescue System (NSRS) in order to establish an international submarine rescue vessel classification. The NSRS is an effort to develop multi-national submarine rescue capability between France, Turkey, Norway, and the UK. The concept and operation of the NSRS is similar to the SRDRS, with an ROV type rescue vehicle supported by a "Mother Ship" (MOSHIP) capable of being deployed worldwide. The NSRS requirements are listed and compared to the SRDRS requirements in Table 5.1.

Table 5.1. Summary of Rescue System Required Physical Characteristics (NATO 2004,

Characteristic	NSRS	SRDRS
Deck Space	> 300 m^2 > 10 m usable stern width	> 268 m^2
Deck Load	> 300 tonnes	> 185.9 tonnes (183 LT)
Deck Strength	> 2.5 tonnes/m^3	> 2 tonnes/m^2 (0.19 LT/ft^2)
Seakeeping	-Motion characteristics no more severe than typical for a vessel 60 m in length -Continuous operation in sea state 6	up to Sea State 4, accelerations at head of LARS A-Frame at max aft outreach.

Because the NSRS requirements are generally more restrictive than the SRDRS requirements, basing a vessel classification on the NSRS may exclude some vessels which would be perfectly suitable for the SRDRS. However, a set of class rules which does cover both systems would be more likely to be adopted by more classification societies, especially internationally based classification societies.

Developing classification rules for any or all of the world's classification societies will greatly aid in the rapid selection of VOOs. Additionally, having a supplementary class for submarine rescue system support vessels will contribute to awareness among vessel owners and operators. That awareness would aid actual rescue efforts since the owners and operators would be more familiar with the nature ofa submarine rescue system and what to expect operationally.

5.3.3. Design and build to SRDRS requirements

The option to encourage vessel builders and owners to include the VOO requirements in the construction of their new vessels is similar to the classing option except that it requires a direct interface with the owners and builders. Additionally, some motivation or incentive may be required. This option would probably be most successful with U.S. shipbuilders where constructing "submarine rescue capable" vessels would be a matter of patriotism and civic pride.

Above a certain size of vessel, the requirements would probably not appreciably change the design of the vessel. But, for the borderline cases like the T-ATF, the VOO requirements may enable designs to be only slightly modified in the design stage to ensure operational

adequacy. Unlike the option of classing the vessels for VOO adequacy where the classing societies would inspect engineering drawings and survey vessels to enforce the class rules, motivating shipbuilders to design and construct vessels to the VOO requirements would require an enforcement or certification mechanism. As with a classification society, drawings, plans and vessels under construction would all have to be inspected to ensure the requirements are being met.

While a disabled submarine incident could occur anywhere in the world, the frequency of such incidences is quite low meaning that the SRDRS will likely be used more often in testing and training exercises than actual rescue missions. Having a ready fleet of U.S. based vessels which are built to meet the VOO requirements could be of great value if only to support testing and training exercises. Although establishing classing rules would accomplish the same thing, the design and build to requirements option could potentially be implemented in a shorter amount of time than the classing option.

5.4. Conclusion

Some form of the first option, developing a comprehensive database of qualified VOOs, will likely have the greatest impact on reducing the time it takes to evaluate and select VOOs which, in turn, directly impacts how quickly the whole SRDRS system can be deployed. Implementing a special classification for submarine rescue capable vessels, if only with a few classification societies, would make the selection of VOOs somewhat easier. But, the information on which vessels are classed as VOO capable would still have to be maintained in some sort of a database. If either of the last two options is implemented, the greatest benefit would be in augmenting the data already in a VOO database.

Chapter 6. CONCLUSIONS AND FUTURE WORK

6.1. VOO Selection

The Submarine Rescue Diving and Recompression System represents a significant improvement in the submarine rescue capability not previously available to the U.S. Navy. This capability can only be deployed on VOOs which can successfully support full operations of the SRDRS. System success on a rescue mission also hinges on the rapid selection of the VOO. In order to facilitate that rapid selection, this thesis developed the necessary theoretical background for a procedure that uses only limited vessel characteristics to evaluate potential VOOs for stability and seakeeping suitability. This procedure begins by developing hull geometry and an empirically derived weight distribution. The derived geometry and weight distribution serve as the inputs for stability analysis at several different load cases and the seakeeping analysis. The efficacy of this VOO evaluation process is demonstrated by comparing results to known stability and seakeeping analyses for the T-ATF, and with a sensitivity analysis of assumed variables. Finally, this thesis explored some of the larger issues involved in rapidly selecting a VOO and deploying the whole SRDRS.

6.2. Future Work and Refinements

The process of developing this procedure uncovered many other issues and subjects for further development that could benefit this procedure and its utility to the SRDRS. The areas recommended for future work include:

- Refine procedure assumptions. Certain assumptions used for this procedure, especially for hull coefficients and VCG, could be refined and improved with collection of more actual ship data.
- Conduct a more extensive sensitivity analysis with a variety of vessels including barges. The sensitivity analysis performed for this thesis uncovered basic trends in the variables that were explored. But, a more comprehensive sensitivity analysis could improve the assumptions underlying the theory as well as guiding how to change assumptions for different ship types.

- Although the procedure can be executed manually quite rapidly, automation of the step-by-step process using macros or a standalone program could greatly speed the process. User input and supervision would still be required at certain steps in the process (such as hull generation). Automation of the process could also allow quicker evaluation of large groups of ship databases.

6.3. Conclusion

The rescue of the Squalus and the more recent tragedy of the Kursk have shown that submariners can survive in a disabled and bottomed submarine. Their survival time is measured in hours or, at best, a few short days. Even in the best scenario, the rescue mission may still be arriving on scene at the very last moments of survival for the submariners making the rapid deployment of the system that much more critical. The SRDRS has been designed for rapid transport from its homeport in San Diego to anywhere in the world. But, quick deployment is meaningless unless the destination, a Vessel of Opportunity, can also be rapidly identified and analyzed for adequacy.

The procedure developed in this thesis provides a good means of rapidly and accurately assessing the adequacy of a potential VOO using only limited vessel characteristics. From the basic vessel characteristics, vessel geometry and weight distribution are created to serve as inputs to the stability and seakeeping analyses. As the SRDRS is fielded, the underlying requirements for VOO adequacy will probably be changed and refined. The theory and methods underlying this procedure, however, remain valid even when using the updated requirements. With familiarity, this procedure could be executed to analyze a vessel in less than an hour allowing an adequate VOO to be quickly selected. Rapid assessment of adequacy directly impacts the ability to quickly charter the necessary VOO and deployment of the SRDRS to exactly where it is needed (though it could conceivably depart and be directed to the VOO enroute). In a matter of hours, help can be on the way to rescue submariners who will benefit from the efforts of Admiral Momsen and all those who followed him.

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APPENDIX A. VOO SELECTION PROCEDURE

1. Introduction and Setup

1.1. Procedure Conventions

For the sake of brevity, "potential VOOs" may also be referred to as "the ship" within this procedure. English units are used since this is the system that the SRDRS uses, however each of the programs that are used do support SI units. The step-by-step process described in this chapter will use the T-ATF as an example case.

The various steps that are required for this procedure are indicated as follows:

- Actions are indicated in bold-italics: ***click, select***, etc…
- File names and required data entry will be in quotes: **"filename.mdl"**
- Menu items and trees or tabs within a window will be indicated as follows: **[File]>[Save]**

1.2. Programs Utilized for Selection Procedure

The following are the databases and programs that are used for this procedure:

- OPL-AHTS Database
- ASSET 5.0.0
- POSSE Ship Project Editor
- POSSE 4
- POSSE SMP

1.3. Information required for analysis

Table A.1 lists the minimum potential VOO information that is required to perform this analysis.

Table A.1. Parameters Required for VOO Analysis

Parameter		Tutorial Values for T-ATF
LOA	Length Over All	200 ft
B	Beam	42 ft
T	Draft	15.5 ft
D	Depth	25 ft (illustrative tutorial value)
DWT	Dead Weight Tonnage	814 LT
The following are not required for stability or seakeeping analysis, but are required for an initial geometry check that the deck is capable of carrying the SRS		
Deck Length		89 ft
Deck Width		30 ft
Deck Cargo		296 LT
Deck Strength		2 tonnes/m^2

1.4. Criteria For Adequacy

Table A.2 lists the criterion against which the results of this procedure will be compared in SI units with English units in parenthesis. Also indicated is whether that value is the minimum or maximum value allowed.

Table A.2. Criteria for VOO Adequacy

Parameter	**Value**
DECK GEOMETRY for full SRDRS (NAVSEA 1, 2, 11)	
Deck Length (min)	29.3 m (96 ft)
Deck Width (min)	9.14 m (30 ft)
Deck Cargo (min)	185.5 tonnes (182.6 LT)
Deck Strength (min)	2 tonnes/m^2 (0.19 LT/ft^2 = 2.8 psi)
STABILITY (IMO Resolution A.749(18)-3.1 (A.167), General Intact Stability Criteria for All Ships)	
GZ vs Angle of Heel:	
Area to 30 deg (min)	0.05 m-rad (9.4 ft-deg)
Area to 40 deg (min)	0.09 m-rad (16.92 ft-deg)
Area 30 to 40 deg (min)	0.03 m-rad (5.64 ft-deg)
Angle at Max GZ (min)	25 deg
Max GZ	0.2 m (0.66 ft)
Initial GM (min)	0.15 m (0.49 ft)
SEAKEEPING, up to Sea State 4, accelerations at head of LARS A-Frame at max aft outreach. (John J. McMullen Associates, 7, 8)	
Longitudinal Acceleration (max)	0.20 g
Transverse Acceleration (max)	0.39 g
Vertical Acceleration (max)	0.31 g

The Deck Geometry criteria are based on the physical size requirements of the complete SRDRS installed on a VOO. The Stability criteria, IMO Resolution A.749(18)-3.1 (A.167), are used since they provide a good, general set of criteria. If desired, other criteria can be added or substituted within POSSE 4. The Seakeeping criteria are based on an initial seakeeping analysis performed on the T-ATF. Since the results of this seakeeping analysis were used for the design of the SRDRS including the LARS A-frame and associated deck templates (where the LARS is attached), these accelerations served as the limiting case. Once the SRDRS is complete these values could be updated.

2. VOO Selection Procedure

The following step-by-step procedure utilizes the T-ATF as a numerical example.

2.1. Verify Deck Geometry

- *Verify* that the ship's deck length, deck width, deck cargo capacity and deck strength are all less than the criteria listed in Table A.3.

Table A.3. Deck Geometry Criteria

Parameter	Value
DECK GEOMETRY(NAVSEA 1, 2, 11)	
Deck Length (min)	29.3 m (96 ft)
Deck Width (min)	9.14 m (30 ft)
Deck Cargo (min)	185.5 tonnes (182.6 LT)
Deck Strength (min)	2 tonnes/m^2 (0.19 LT/ft^2 = 2.8 psi)

2.2. Generate Hull Geometry

- Ship File Creation
  - *Open* ASSET, *select* **the "MONOSC" module**
  - *Select* the desired databank, either the default "msc500.bnk" or any other user created databank.
  - ASSET uses SI units by default, if English units are required (as in the case of the T-ATF illustration), *select* **[Options]>[Change Units to: English]**
  - *Select* **[File]>[Save],** *enter* the desired **"filename"** in the topmost databank field. *Click* **[OK]**

- Hull Characteristics Entry
    - *Select* **[Edit]>[Open Editor]**, the Editor table will be displayed as shown in Figure A.1. Data fields can be found by either clicking down the required field tree on the left or by entering the field name in the search box at the top of the editor.

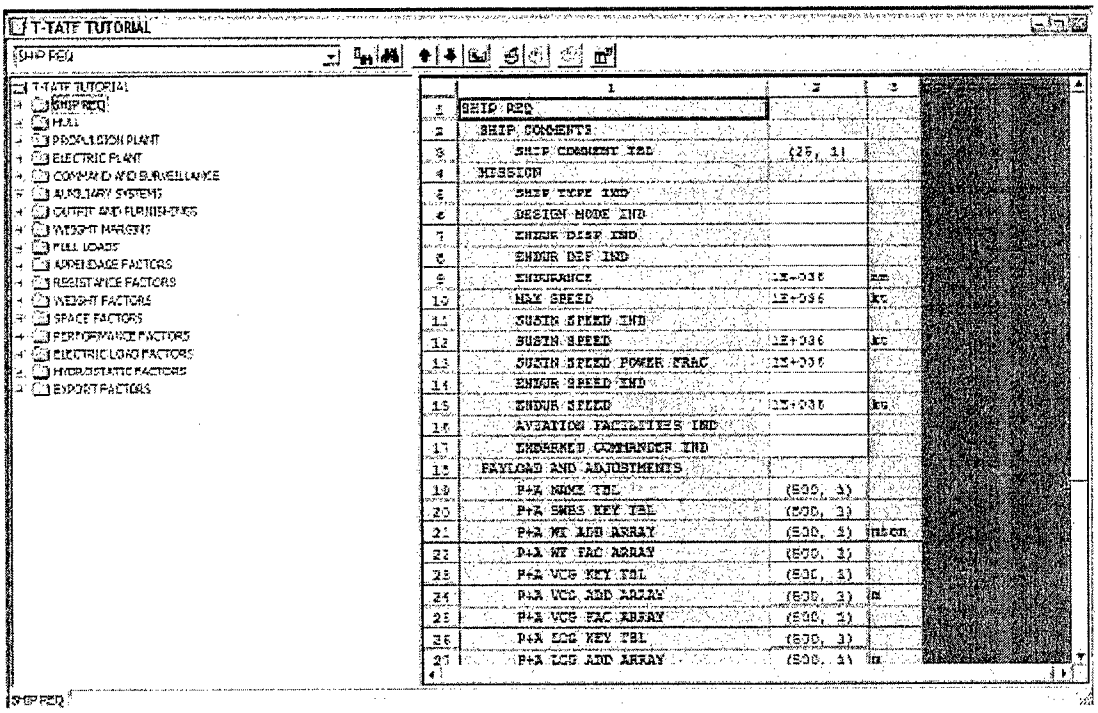


Figure A.1. ASSET Editor

- *Enter* the data in Table A.4 in their respective fields. Data in brackets ([data]) indicates data that will be ship specific.

Table A.4. Data for ASSET Hull Generation

Field	Value	Units
SHIP TYPE IND	TENDER	
HULL OFFSETS IND	GENERATE	
HULL DIM IND	NONE	
MIN BEAM	[42]	ft
MAX BEAM	[42]	ft
STABILITY IND	2/3	
HULL FLARE ANGLE	0	deg
LBP	[195]	ft
BEAM	[42]	ft
DRAFT	[14.95]	ft
DEPTH STA 0[1]	[25]	ft
DEPTH STA 3	[25]	ft
DEPTH STA 10	[25]	ft
DEPTH STA 20	[25]	ft
PRISMATIC COEF[2]	0.716 (0.729)	
MAX SECTION COEF	0.893 (0.906)	
WATERPLANE COEF	0.770472	
LCB/LBP	0.5	
LCF/LBP	0.5	
MAIN DECK HT	[25]	ft
HULL BC IND	AUX CLOSED[3]	
HULL STA IND	OPTIMUM	

  - *Save, Close* the editor.

- HULLGEN offset generation
  - *Select* **[Module]>[Run]**
  - *Select* **[Synthesis Modules]>[X HULL GEOM MODULE]**
  - *Click* **[Reports]**
  - *Select* **[Printed Reports]>[1 - Summary]**
  - ***CTRL-click*** **[Graphic Reports]>[1 - Body Plan] and [2 - Hull Isometric View]**

[1] Although known depth is the midship depth, a higher depth for forward stations can be estimated without affecting the results of the stability and seakeeping analysis. Based on the T-ATF, the varying depth at the stations could also be estimated as: D0=1.8*D20; D3=1.7*D20, D10=1.5*D20; D20=D.

[2] Coefficients are actual T-ATF values, parenthetical values are based on typical values for offshore supply vessels from SNAME PNA vol. I

[3] Change this value to **"Given"** if different D0, D3, D10 and D20 are desired

- o *Click* **[RUN]**
- o The hull geometry module should run, correct any errors as required based on error messages in the ASSET prompt window.
- o For the purposes of this analysis, LBP must be estimated from LOA. Because detailed information for LBP is often not available and the vessels in question typically have a full hull form, the LBP should be estimated to be 10-15% less than the LOA. The final LBP can be iterated after generating the hull in order to get the ASSET generated hull LOA to match the published LOA.

- Verification of offset generation
  - o after successfully running the hull geometry module, the graphical reports will be displayed as shown in Figure A.2 and Figure A.3. ***Click*** on the report to progress to the next report and to the end of the graphical reports. Verify that the hull shape has consistency and no anomalies (errant bulges, odd shapes, etc.). At the end of the Graphic Reports, c***lick*** **[OK]**

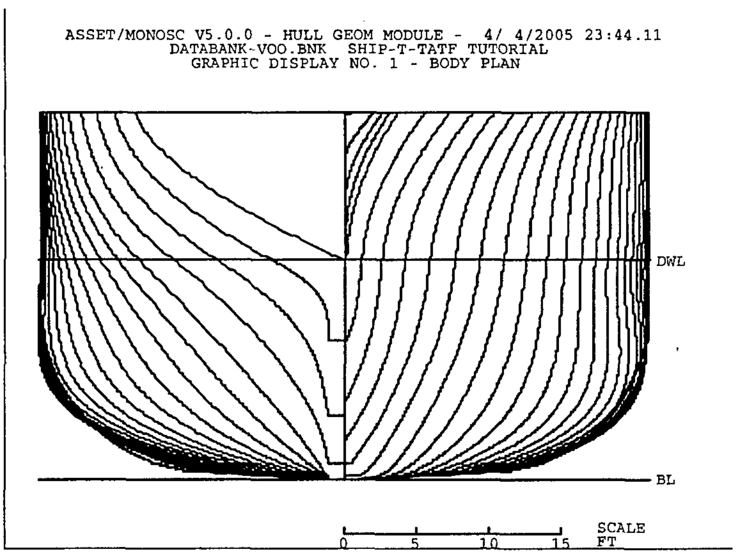


Figure A.2. ASSET Body Plan Output

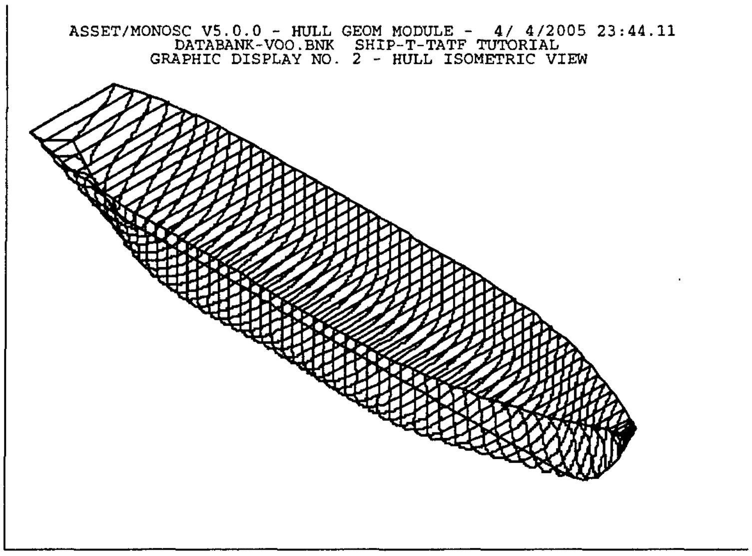


Figure A.3. ASSET Hull Isometric View

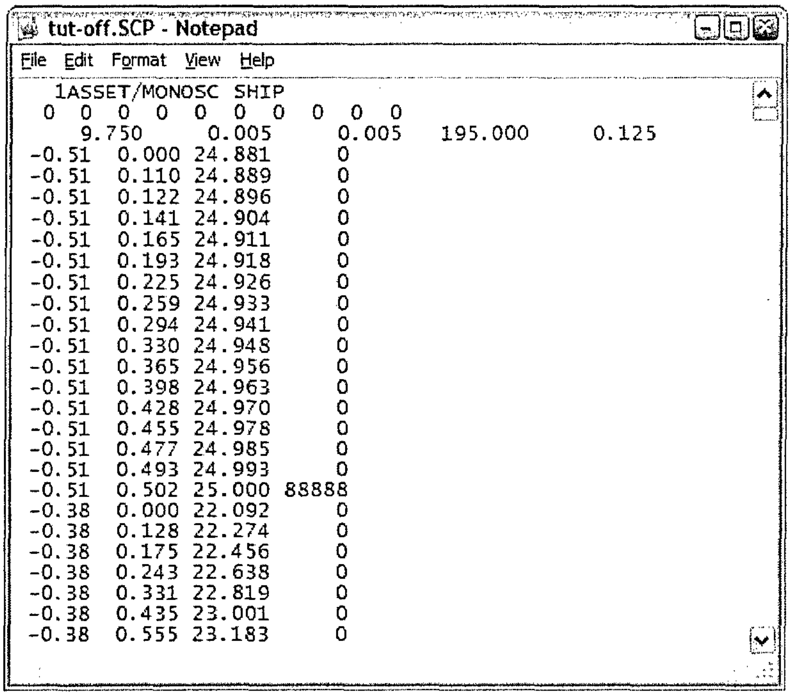
- ***Select* the [Printed Reports] window**
- You should see "Printed Report No. 1", shown in Table A.5, verify that all the parameters are as desired.

Table A.5. Asset Printed Report

```
      ASSET/MONOSC V5.0.0 - HULL GEOM MODULE -  4/ 5/2005  0: 1.18
                     DATABANK-VOO.BNK  SHIP-T-TATF TUTORIAL


PRINTED REPORT NO.  1 - HULL GEOMETRY SUMMARY


HULL OFFSETS IND-GENERATE                    MIN BEAM, FT                 42.00
HULL DIM IND-NONE                            MAX BEAM, FT                 42.00
MARGIN LINE IND-CALC                         HULL FLARE ANGLE, DEG          .00
HULL STA IND-OPTIMUM                         FORWARD BULWARK, FT           4.00
HULL BC IND-AUX CLOSED

                  HULL PRINCIPAL DIMENSIONS (ON DWL)
                  ==================================
LBP, FT                           195.00     PRISMATIC COEF               0.716
HULL LOA, FT                      199.97     MAX SECTION COEF             0.893
BEAM, FT                           42.00     WATERPLANE COEF              0.770
BEAM @ WEATHER DECK, FT            42.37     LCB/LBP                      0.508
DRAFT, FT                          14.95     HALF SIDING WIDTH, FT         1.00

DEPTH STA 0, FT                    25.00     BOT RAKE, FT                  0.00
DEPTH STA 3, FT                    25.00     RAISED DECK HT, FT            0.00
DEPTH STA 10, FT                   25.00     RAISED DECK FWD LIM, STA
DEPTH STA 20, FT                   25.00     RAISED DECK AFT LIM, STA
FREEBOARD @ STA 3, FT              14.05     BARE HULL DISPL, LTON      2236.96

STABILITY BEAM, FT                 44.77     AREA BEAM, FT                19.50

      BARE HULL DATA ON LWL                        STABILITY DATA ON LWL
      =====================                        =====================
LGTH ON WL, FT                    194.98     KB, FT                        8.29
BEAM, FT                           41.99     BMT,  FT                      9.85
DRAFT, FT                          14.93     KG,  FT                      15.00
FREEBOARD @ STA 3, FT              14.07     FREE SURF COR, FT             0.00
PRISMATIC COEF                     0.701     SERV LIFE KG ALW, FT          0.00
MAX SECTION COEF                   0.912
WATERPLANE COEF                    0.778     GMT, FT                       3.13
WATERPLANE AREA, FT2             6367.35     GML, FT                     166.19
WETTED SURFACE, FT2              9784.28     GMT/B AVAIL                  0.075
                                             GMT/B REQ                    0.100
BARE HULL DISPL, LTON            2235.52
APPENDAGE DISPL, LTON               8.28
FULL LOAD WT, LTON               2243.80
```

- Export Hull Offsets
  - *Select* **[Utilities]>[Export…]**
  - *Select* **[Export Target]: "SHCP"**
  - *Click* **[Browse]**
  - *Select* the file location you wish to save to, *enter* **"filename".scp**

- *Click* [Save]
- *Click* [OK]
- ***Save, close*** ASSET
- ***Open*** the **"filename.scp"** file in **"Notepad"** or some other text editor. You should see the offset data as shown in Figure A.4.

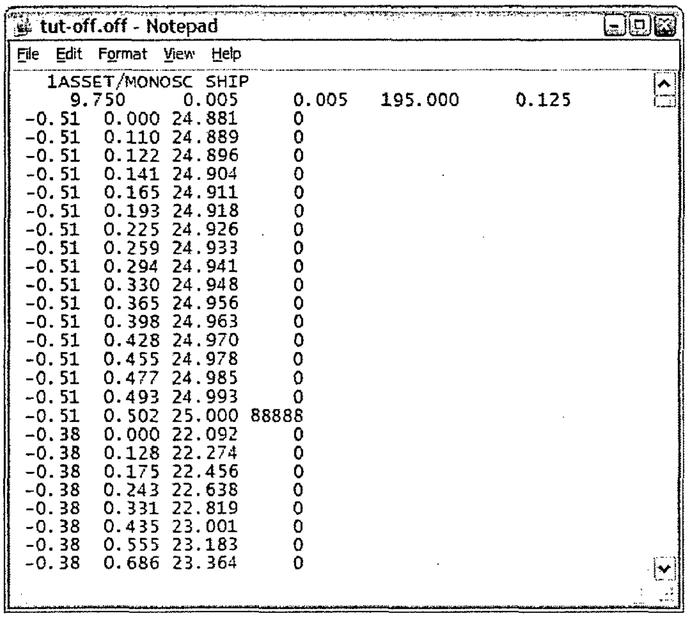

tut-off.SCP - Notepad

File Edit Format View Help

```
  1ASSET/MONOSC SHIP
 0  0  0  0  0  0  0  0  0  0
    9.750      0.005      0.005   195.000      0.125
-0.51  0.000 24.881      0
-0.51  0.110 24.889      0
-0.51  0.122 24.896      0
-0.51  0.141 24.904      0
-0.51  0.165 24.911      0
-0.51  0.193 24.918      0
-0.51  0.225 24.926      0
-0.51  0.259 24.933      0
-0.51  0.294 24.941      0
-0.51  0.330 24.948      0
-0.51  0.365 24.956      0
-0.51  0.398 24.963      0
-0.51  0.428 24.970      0
-0.51  0.455 24.978      0
-0.51  0.477 24.985      0
-0.51  0.493 24.993      0
-0.51  0.502 25.000  88888
-0.38  0.000 22.092      0
-0.38  0.128 22.274      0
-0.38  0.175 22.456      0
-0.38  0.243 22.638      0
-0.38  0.331 22.819      0
-0.38  0.435 23.001      0
-0.38  0.555 23.183      0
```

Figure A.4. ".scp" Offsets File

- ***Delete*** the second line (the line with all zeros). ***Save-as*** **"filename.off"**; ensure that the filename has only the ".off" extension. If necessary, change the filename manually in "Explorer". The result should appear as Figure A.5.



tut-off.off - Notepad

File Edit Format View Help

```
  1ASSET/MONOSC SHIP
    9.750      0.005      0.005   195.000      0.125
 -0.51  0.000 24.881      0
 -0.51  0.110 24.889      0
 -0.51  0.122 24.896      0
 -0.51  0.141 24.904      0
 -0.51  0.165 24.911      0
 -0.51  0.193 24.918      0
 -0.51  0.225 24.926      0
 -0.51  0.259 24.933      0
 -0.51  0.294 24.941      0
 -0.51  0.330 24.948      0
 -0.51  0.365 24.956      0
 -0.51  0.398 24.963      0
 -0.51  0.428 24.970      0
 -0.51  0.455 24.978      0
 -0.51  0.477 24.985      0
 -0.51  0.493 24.993      0
 -0.51  0.502 25.000  88888
 -0.38  0.000 22.092      0
 -0.38  0.128 22.274      0
 -0.38  0.175 22.456      0
 -0.38  0.243 22.638      0
 -0.38  0.331 22.819      0
 -0.38  0.435 23.001      0
 -0.38  0.555 23.183      0
 -0.38  0.686 23.364      0
```

Figure A.5. "*.off" Modified File

- *Close*

2.3. Development of POSSE Ship Model

2.3.1. Hull Geometry

- Create Ship Model
  - *Open* **POSSE Ship Project Editor**
  - In the **[Open Ship Project]** dialog box, s*elect* the **[New] tab**
  - ***Select* units = "ft"**
  - ***Enter* [Name] = "shipname"**
  - ***Enter* [Particulars]>[LBP] = "195", [Beam] = "42", [Depth] = "25"**
  - The final dialog box should appear as shown in Figure A.6.
  - ***Click* [OK]**

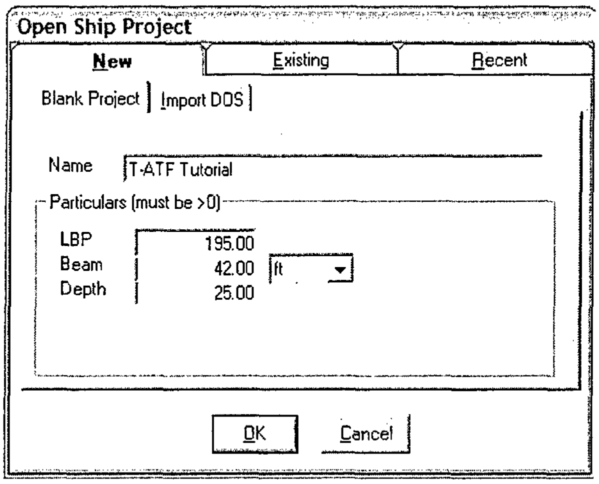


Figure A.6. Entry of New Ship Project Particulars

- Import Hull Offsets
- ***Select*** **[File]>[Import]**
- ***Select*** **[Files of Type] = "SHCP Hull Offsets (*.off)"**
- ***Browse and select*** the hull offsets created earlier, **"filename.off"**
- ***Click*** **[OK]**
- ***Verify*** that your hull geometry has been imported as expected, in the model tree in the left view plane ***select*** **[Geometry]>[Hull]** to view the stations, offsets and particulars as shown in Figure A.7.

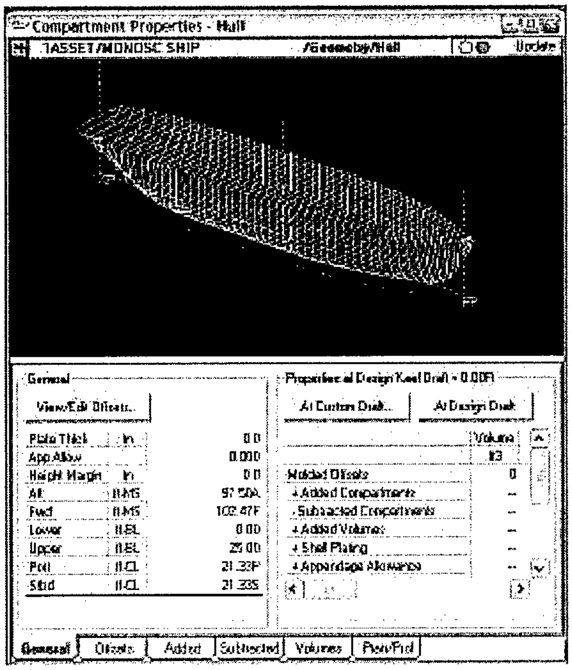


Figure A.7. Verification of Imported Hull Geometry

- o *Select* **[File]>[Save]: [File Name] = "filename.shp"**

2.3.2. Curves of Form

This step creates the Hydrostatic curves of form, Bonjean curves, and Cross Curves of stability.

- ***Select*** **[Tables]>[Generate Hydrostatics ...],** ***click*** **[Generate]**
- ***Select*** **[Tables]>[Generate Bonjeans ...],** ***click*** **[Generate]**
- ***Select*** **[Tables]>[Generate Cross Curves ...],** ***click*** **[Generate]**
- ***Verify*** that the curves were successfully created, to view the tables in the model tree in the left view plane:
    - o ***select*** **[Tables]>[Hydrostatic Tables]>[Unnamed]**
    - o ***select*** **[Tables]>[Bonjean Tables]>[Unnamed]**
    - o ***select*** **[Tables]>[Cross Curve Tables]>[Unnamed]**
- ***Save***

2.3.3. Lightship Weight Distribution

This step assumes that the lightship weight is unknown and will have to be derived from known draft and DWT. If the lightship weight is known, the derivation can be skipped and the weight entered directly into the ship model in the Ship Project Editor.

- Lightship Weight Derivation
  - *Close* **POSSE Ship Project Editor**
  - *Open* **POSSE 4**
  - In the select ship dialog box, ***select*** the "*.shp" file you have created: **"filename.shp"**
  - *Click* **[OK]**
  - *Click* **[Ignore All]** for any error messages.
  - *Open* or ensure that the following windows are open: **[Tankage and Cargo Entry], [Intact Trim and Stability Summary]** and **[Profile and Plan Intact].** The workspace should appear as shown in Figure A.8.

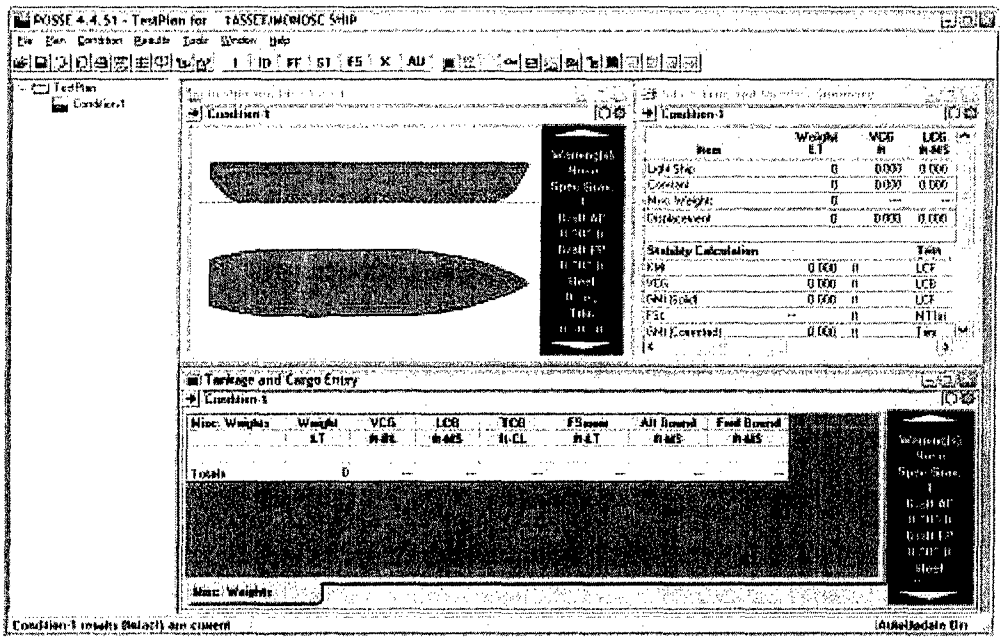
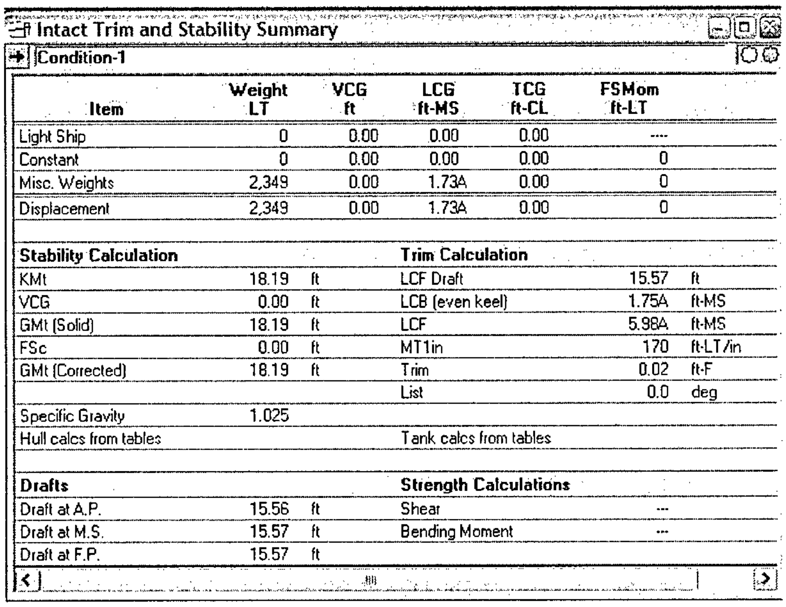


Figure A.8. POSSE 4 Workspace

- In the **[Tankage and Cargo Entry] table,** ***Enter*** the name **[Misc. Weights]** = **"DWT"**, and **[Weight LT]** = **"[814]"** (this is the known DWT from the OPL Database). VCG does not matter at this point of developing the model. This DWT is applied at midships and the lightship weight iteration will develop the necessary LCG offset to give the ship a even keel.
- ***Enter*** the name **[Misc. Weights] = "LS"**, and iterate on **[Weight LT]** = **"X"** and **[LCG (ft-MS)]= "+/- XX"** (- for forward of MS, + for aft of MS) to achieve the draft specified in the OPL Database on an even keel. For this T-ATF example, the **[Intact and Trim Stability Summary]** should appear as Figure A.9, and the **[Tankage and Cargo Entry]** should appear as Figure A.10.



Intact Trim and Stability Summary

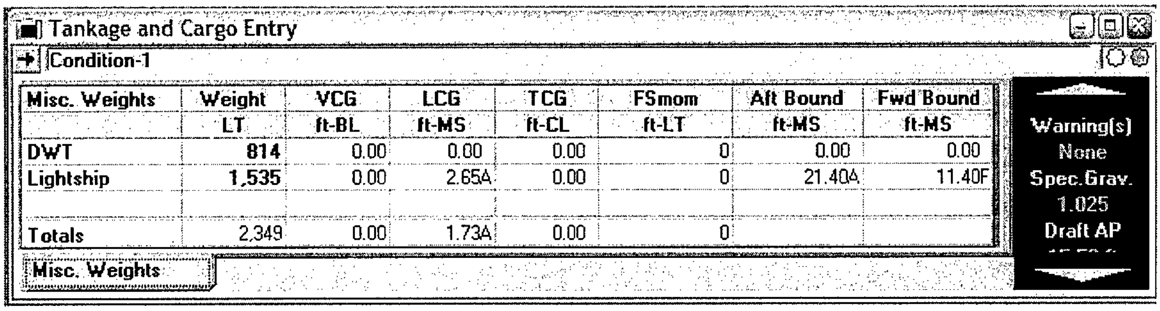
Condition-1

Item	Weight LT	VCG ft	LCG ft-MS	TCG ft-CL	FSMom ft-LT
Light Ship	0	0.00	0.00	0.00	----
Constant	0	0.00	0.00	0.00	0
Misc. Weights	2,349	0.00	1.73A	0.00	0
Displacement	2,349	0.00	1.73A	0.00	0

Stability Calculation			Trim Calculation		
KMt	18.19	ft	LCF Draft	15.57	ft
VCG	0.00	ft	LCB (even keel)	1.75A	ft-MS
GMt (Solid)	18.19	ft	LCF	5.98A	ft-MS
FSc	0.00	ft	MT1in	170	ft-LT/in
GMt (Corrected)	18.19	ft	Trim	0.02	ft-F
			List	0.0	deg
Specific Gravity	1.025				
Hull calcs from tables			Tank calcs from tables		

Drafts			Strength Calculations	
Draft at A.P.	15.56	ft	Shear	---
Draft at M.S.	15.57	ft	Bending Moment	---
Draft at F.P.	15.57	ft		

Figure A.9. Intact and Trim Stability Summary for Lightship Weight Derivation



Tankage and Cargo Entry

Condition-1

Misc. Weights	Weight LT	VCG ft-BL	LCG ft-MS	TCG ft-CL	FSmom ft-LT	Aft Bound ft-MS	Fwd Bound ft-MS
DWT	814	0.00	0.00	0.00	0	0.00	0.00
Lightship	1,535	0.00	2.65A	0.00	0	21.40A	11.40F
Totals	2,349	0.00	1.73A	0.00	0		

Warning(s)
None
Spec.Grav.
1.025
Draft AP

Misc. Weights

Figure A.10. Tankage and Cargo Entry for Lightship Weight Derivation

- ***Record*** the weight and LCG of this Lightship for later entry into the ship model in the Ship Project Editor.
- ***Close*** **POSSE 4**

- Apply Lightship Weight
  - ***Open*** **POSSE Ship Project Editor,** ***open*** the ship project that was used earlier: **"filename.shp"**
  - ***Select*** **[Loads]>[Lightship]**
  - ***Enter*** the lightship weight and, LCG and that was derived in the previous step: **[Magnitude Weight LT] = "1535", [LCG ft-MS] = "-2.65 "**
  - ***Enter*** the VCG location as **0.975** of the depth (although this example used a depth of 25 ft for illustrative purposes to generate the hull, the actual T-ATF depth is 20 ft, that depth is used for this VCG): **[VCG] = "19.5"**. This VCG is a conservative estimate based on the T-ATF's lightship weight VCG (19.39 ft actual) (USCG 4). Since the T-ATF is a borderline case for a VOO, the end stability is especially sensitive to the selection of VCG. This high lightship weight will be somewhat mitigated later by adding fuel and water loads which have lower VCGs.
  - The lightship weight entry is shown in Figure A.11.

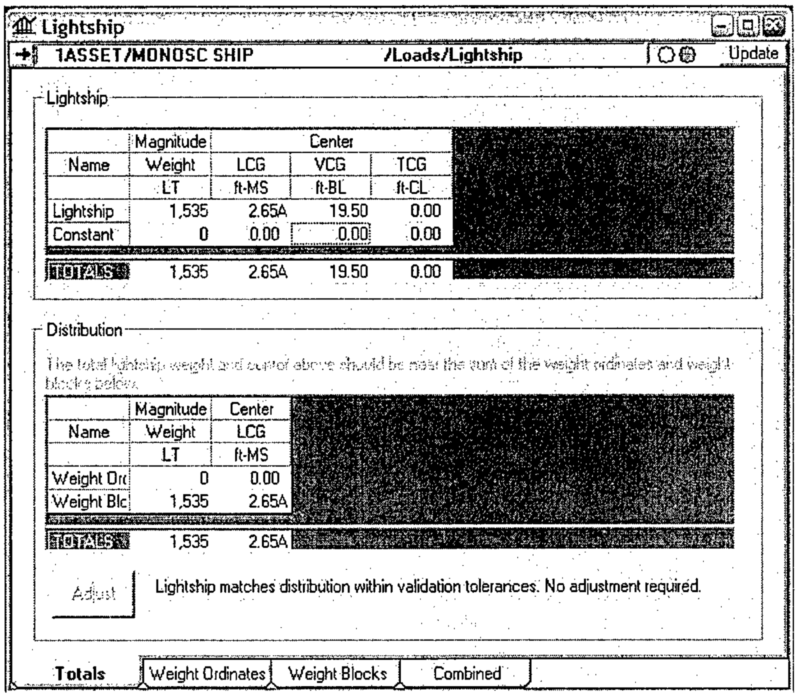


Figure A.11. Lightship Weight Entry

- Apply Lightship weight distribution. This step applies a typical weight distribution using the gross lightship weight based on a parametric model within POSSE Ship Project Editor (HEC).
  - ***Select* [Loads]>[Generate Lightship Distribution]>[From Ship Type…]. *Select* [General Ship] tab.** Adjust the table entries as required based on the know information or to match Figure A.12. While entering the engine horsepower is possible if the information is available, it is not required.

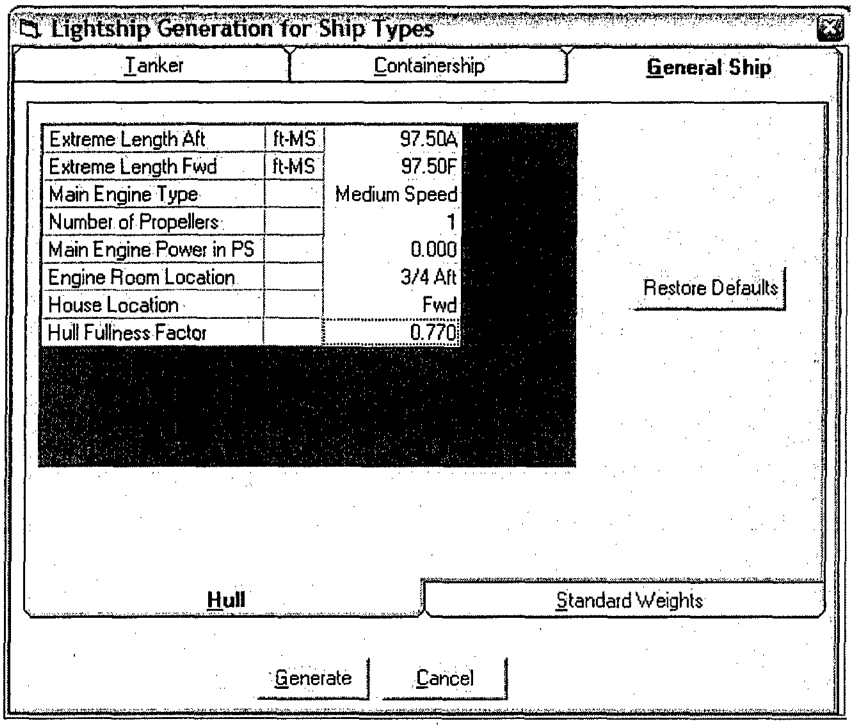


Figure A.12. Lightship Weight Distribution Generation

- *Click* **[Generate]**.
- Verify that the lightship weight has been distributed. ***Select* [Loads]>[Lightship], select the [Combined] tab**. The distribution should appear similar to Figure A.13.

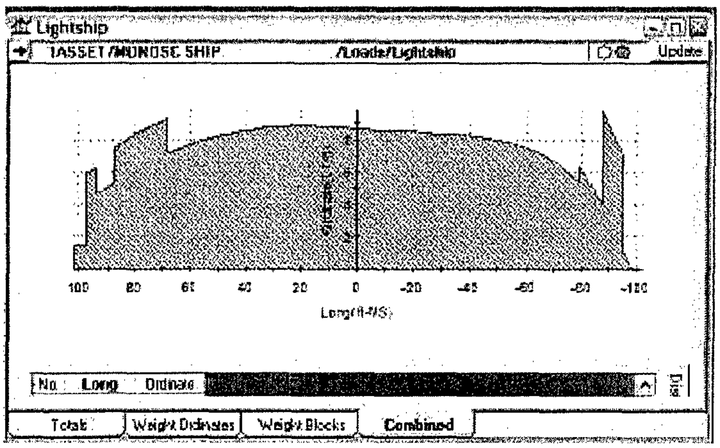


Figure A.13. Lightship Weight Distributed

- *Save* the ship model.

- Validate the ship model for stability analysis
  - ***Select*** **[Validate]>[Model Review]**
  - Correct model errors as necessary so that the **[Available Analysis] tab** has a check next to both **"Trim and Stability (from tables)"** and **"Trim and Stability (from offsets)".**
  - An example of a possible error (one that arose with this tutorial), is the "Weight Block 1". To correct, ***select*** **[Loads]>[Lightship],** ***select*** **the [Weight Blocks] tab,** and ***delete*** weight block 1.
  - ***Save*** the ship model.

2.4. Stability Analysis in POSSE

2.4.1. Loading Plan and Loading Conditions

- ***Open*** **POSSE 4,** ***open*** the ship model that was just created: **"filename.shp"**
- Save the loading plan: ***select*** **[File]>[Save]: "filename.pln"**
- Although the arrangement of the POSSE workspace is subject to user preference, this tutorial uses the following windows: **[Righting Arm Summary], [Intact Trim and Stability Summary], [Tankage and Cargo Summary], [Profile and Plan Intact].** With the view set to **[Window]>[Auto Tile]**, the POSSE viewpane should appear similar to Figure A.14.

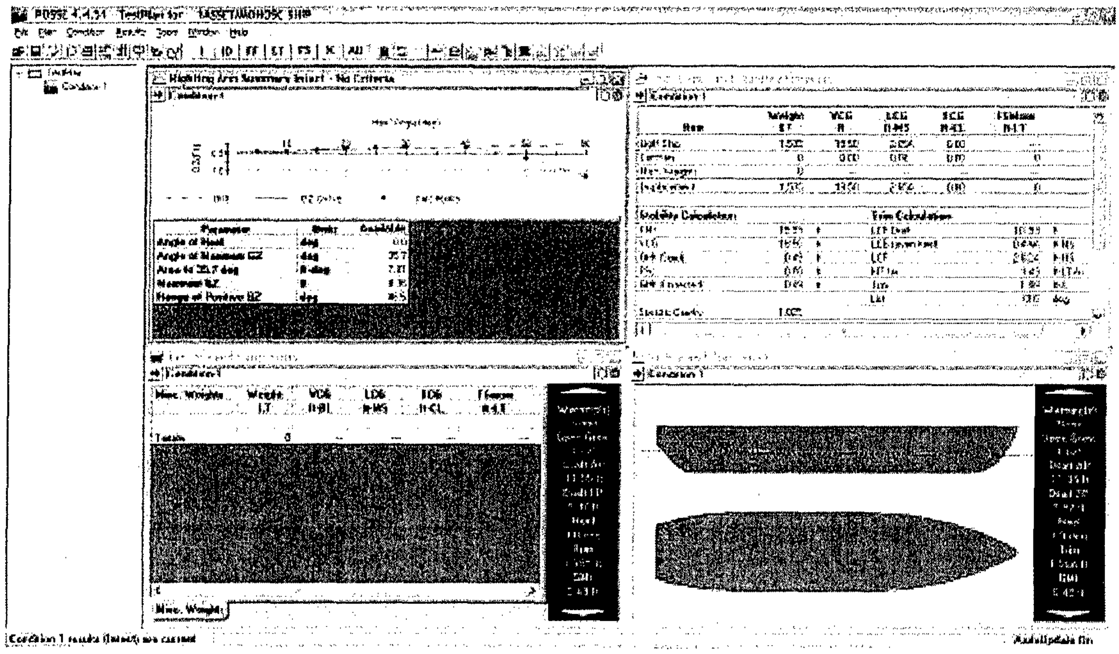


Figure A.14. POSSE Workspace

- Defining Loading Plans. This analysis will define three load plans for the stability analysis: Lightship with SRS, Minimum Operating with SRS and Full Load with SRS. More can be defined if so desired.
    - ***Right-click* "Condition-1", *select* [rename], *enter* "Lightship w/ SRS"**
    - To add the SRS load, in the **[Tankage and Cargo Entry] viewpane, *enter* [Misc. Weights] = "SRS"; [Weight LT] = "183"; [VCG] = 8.69 ft + Depth at Station 20** (this is the worst case position with for the LARS), **in** this case **[VCG] = "33.69"; LCG = 41.24 ft fwd of the AP**, in this case **[LCG] = "-56.26".**
    - As expected for this example, the T-ATF is a borderline case for supporting the SRS and adding the System in Lightship condition results in a negative GM. This would mean that the T-ATF would have reduce its overall VCG to support the SRDRS
    - Add the additional loads, since this is the lightship condition this load will have no weight: ***enter* [Misc. Weights] = "Added"; [Weight LT] = "0"; [VCG] = 0.4 * Depth at Station 10** (this is estimated to be low since most of this additional loading will be fuel and water tank loads), in this case **[VCG] =**

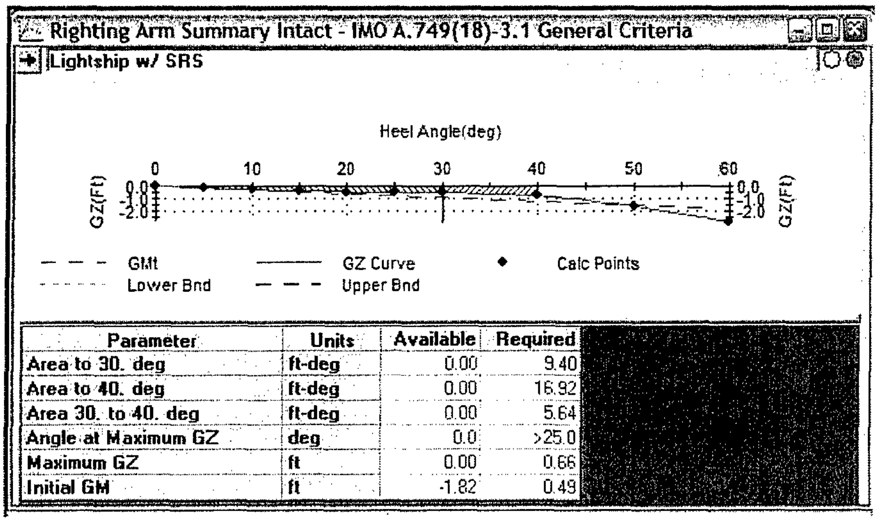
"10"; LCG = LCF (since tank loading can be adjusted for parallel sinkage), in this case **[LCG] = "-6.23"**.

- Apply stability criteria (Table A.6): ***select*** **[Condition]>[Calculation Settings ...]**, ***select*** **[GZ Criteria] tab,** ***select*** **[Select Intact Stability Criterion] = "IMO A.749(18)-3.1 General Criteria",** ***click*** **[OK]**. This is also where other stability criteria can be applied or entered.

Table A.6. Stability Criteria

Parameter	**Value**
STABILITY (IMO Resolution A.749(18)-3.1 (A.167), General Intact Stability Criteria for All Ships)	
GZ vs Angle of Heel:	
Area to 30 deg (min)	0.05 m-rad (9.4 ft-deg)
Area to 40 deg (min)	0.09 m-rad (16.92 ft-deg)
Area 30 to 40 deg (min)	0.03 m-rad (5.64 ft-deg)
Angle at Max GZ (min)	25 deg
Max GZ	0.2 m (0.66 ft)
Initial GM (min)	0.15 m (0.49 ft)

- Export the worst-case stability load case for later use in the seakeeping analysis: ***select*** **[File]>[Export]>[Loadcase (.LC)...]**, ***enter*** the desired file name, ***click*** **[Save].**
- The stability criterion fields are now shown in the **[Righting Arm Summary Intact]** viewpane. Criteria that have failed are highlighted in red as shown in Figure A.15.



Parameter	Units	Available	Required
Area to 30. deg	ft-deg	0.00	9.40
Area to 40. deg	ft-deg	0.00	16.92
Area 30. to 40. deg	ft-deg	0.00	5.64
Angle at Maximum GZ	deg	0.0	>25.0
Maximum GZ	ft	0.00	0.66
Initial GM	ft	-1.82	0.49

Figure A.15. Righting Arm Summary Viewpane

- ***Save*** the ship loading plan.
- Create the remaining loading plans (arbitrary load plans for illustrating this process).
- ***Right-click*** **the plan "Lightship w/ SRS",** ***select*** **[Copy Lightship w/ SRS],** ***rename*** this new plan **"Intermediate".**
- ***Repeat*** the previous step to create the third condition, ***rename*** this condition **"Full Load"**.
- ***Save*** the ship loading plan.
- Enter the Full Load additional weight: ***select*** **the [Full Load]** loading plan from the load plan tree on the left. ***Double-click*** on **[Added]>[Weight LT]** field, ***enter*** **[Weight LT] = DWT less 183 LT for the SRS,** in this case **[Weight LT] = "631".** This is only a gross full weight estimate since fuel tank volumes are not available for all the vessels in the AHTS-OPL database. If that volume is available, the full load weight could also be estimated by calculating the weight of the tanks at 100% full and adding an estimate for stores, fresh water, sea water ballast, etc.
- Enter the Intermediate load additional weight: ***select*** **the [Intermediate]** loading plan from the load plan tree on the left. ***Double-click*** on **[Added]>[Weight LT]** field, ***enter*** **[Weight LT] = half the weight from the Full Load Added weight,** in this case **[Weight LT] = "315.5".** Although this additional weight is somewhat arbitrary

for the intermediate loading case, it does give a good indication of a typical loading that the ship may experience while operating with the SRS.

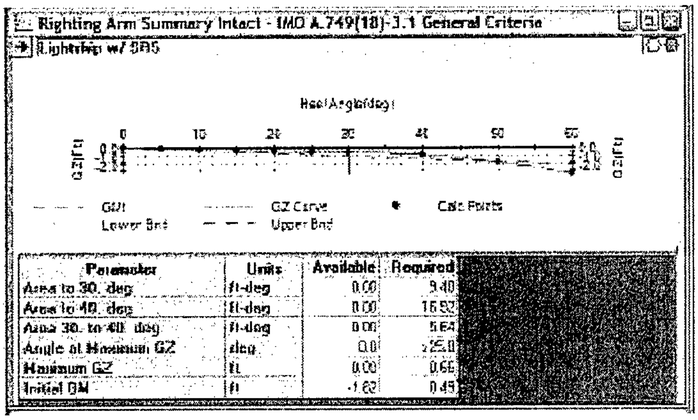
- ***Save*** the ship loading plan.
- Other load plans that can be input and used for analyzing stability are shown in Table A.7. The relative weights, LCGs and VCGs are estimated from the T-ATF loading cases and attempt to account for tankage as lumped weights. Based on load plans analyzed in "Trim and Stability Analysis" (Oceaneering International, Inc. 2003), these plans assume that burned fuel will be compensated with, to a limited extent, seawater ballast. Also assumed is that the seawater tanks are near the baseline and serve to slightly lower the VCG of the additional weight.

Table A.7. Recommended Alternative Load Plans

Alternate Load Plans	Characteristic	Unit	Value
Departure with LARS Vertical	SRS	LT	183
	SRS LCG	ft AFP	41.24 ft fwd of the AP
	SRS VCG	ft ABL	8.69 + D20
	DISSB Crew	LT	0.00
	DISSB Crew LCG	ft AFP	0.00
	DISSB Crew VCG	ft ABL	0.00
	Addl (incl tanks)	LT	DWT × 0.7
	Addl LCG	ft AFP	MS
	Addl VCG	ft ABL	D20 × 0.45
Mid-Voyage with LARS vertical	SRS	LT	183
	SRS LCG	ft AFP	41.24 ft fwd of the AP
	SRS VCG	ft ABL	8.69 + D20
	DISSB Crew	LT	5.16
	DISSB Crew LCG	ft AFP	47 ft fwd of AP
	DISSB Crew VCG	ft ABL	D20 + 6
	Addl (incl tanks)	LT	DWT × 0.5
	Addl LCG	ft AFP	MS
	Addl VCG	ft ABL	D20 × 0.4
Return with LARS vertical	SRS	LT	183
	SRS LCG	ft AFP	41.24 ft fwd of the AP
	SRS VCG	ft ABL	8.69 + D20
	DISSB Crew	LT	5.16
	DISSB Crew LCG	ft AFP	47 ft fwd of AP
	DISSB Crew VCG	ft ABL	D20 + 6
	Addl (incl tanks)	LT	DWT × 0.3
	Addl LCG	ft AFP	MS
	Addl VCG	ft ABL	D20 × 0.3

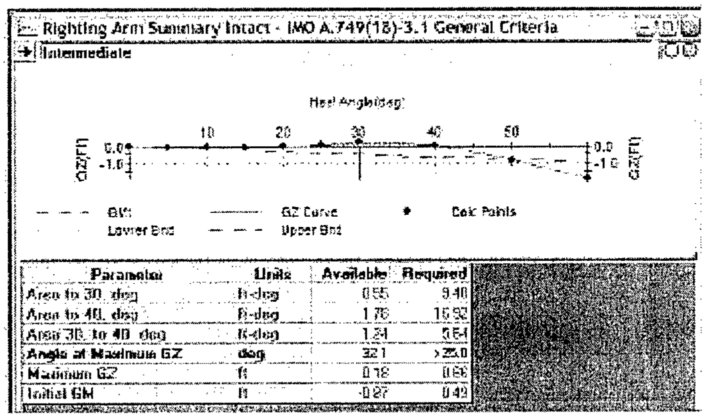
2.4.2. Application and Evaluation for Stability Criteria

The steps above already included application of stability criteria. In this T-ATF example, all the loadings failed the IMO A.749(18)-3.1 General Criteria. Even though the first two loading cases do not even have a positive righting arm, shown in Figure A.16, Figure A.17, and Figure A.18, , the full load case at least has an initial GM=0.14 ft. In order to demonstrate a load case that would pass the stability criteria, ***change*** the **[Added]** load VCG to **[VCG] = "5"**, shown in Figure A.19.



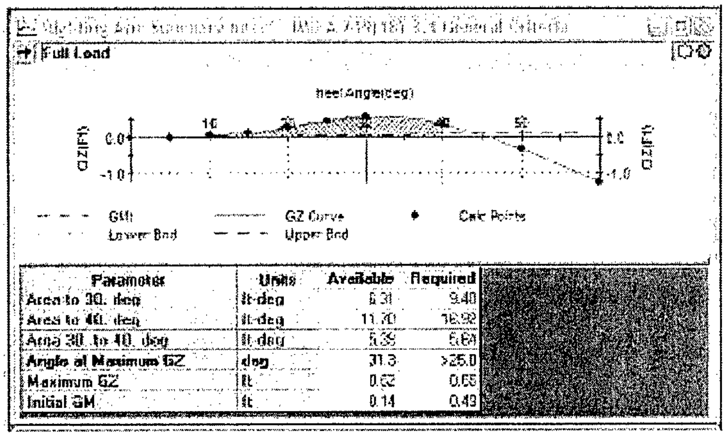
Parameter	Units	Available	Required
Area to 30. deg	ft-deg	0.00	9.40
Area to 40. deg	ft-deg	0.00	16.92
Area 30. to 40. deg	ft-deg	0.00	5.64
Angle at Maximum GZ	deg	0.0	>25.0
Maximum GZ	ft	0.00	0.66
Initial GM	ft	-1.62	0.49

Figure A.16. Lightship Load Case Righting Arm



Parameter	Units	Available	Required
Area to 30. deg	ft-deg	0.55	9.40
Area to 40. deg	ft-deg	1.78	16.92
Area 30. to 40. deg	ft-deg	1.24	5.64
Angle at Maximum GZ	deg	32.1	>25.0
Maximum GZ	ft	0.18	0.66
Initial GM	ft	-0.27	0.49

Figure A.17. Intermediate Load Case Righting Arm



Parameter	Units	Available	Required
Area to 30. deg	ft-deg	6.31	9.40
Area to 40. deg	ft-deg	11.70	16.92
Area 30. to 40. deg	ft-deg	5.39	5.64
Angle at Maximum GZ	deg	31.3	>25.0
Maximum GZ	ft	0.62	0.66
Initial GM	ft	0.14	0.49

Figure A.18. Full Load Case Righting Arm

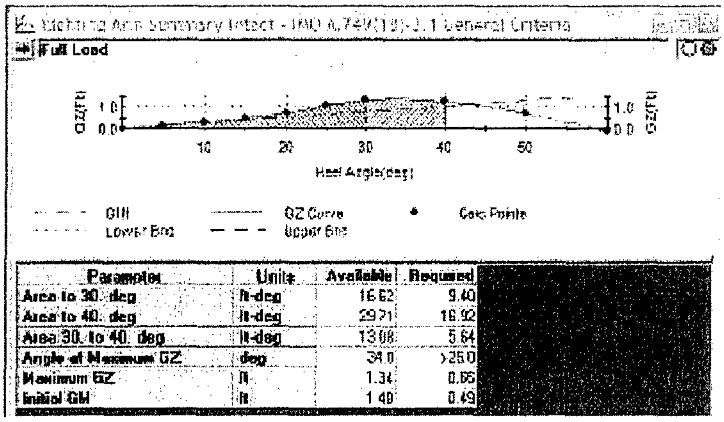


Figure A.19. Modified Full Load Case Righting Arm

2.5. Seakeeping Analysis in POSSE SMP

2.5.1. Importing the POSSE Model into POSSE SMP Preprocessor and Data Preparation

- *Open* the **SMP Preprocessor**
- *Select* **[View]>[Advanced Options]**
- *Select* **[File]>[Save],** *enter* **"filename.smp",** *click* **[Save]**
- To change the units to English units (if necessary): *Select* **[Tools]>[Options]**, in the **[Units and Precision] tab,** *click* **[ft-LT],** *click* **[OK]**
- *Click* **[File]>[Import]>[Offsets from SHP file …],** *browse and select* the **"*.shp"** file that was created with POSSE. *Click* **[OPEN]** to import the offsets.
- To verify that the hull offsets were imported as expected, *click* **[View]>[3D View of Model].**
- *Select* **the [General] tab,** *enter* **[Ship Speed(s)] = "4"**
- Load Case entry using draft, weight distribution and GM data from the POSSE 4 load cases. This example will evaluate the modified Full Load Case (with the Added load VCG lowered to 5 ft), actual evaluation for VOO suitability should examine both the Intermediate and Full Load cases.
    - *Select* **the [Loads] tab**
    - *Select* **[File]>[Import]>[Loadcase],** *select* the desired load case. *Dismiss* any error messages. SMP may only be able to import the lightship distribution, but

it will still simulate the ship motions at the load case draft and will solve for and use the pitch radius of gyration during the SMP run.

  - *Ensure* that the drafts and GM match what you expect, if not:
    - *Enter* the **[Drafts]** at the FP and AP, in this case **[FP] = "18.83", [AP] = "11.88"**
    - *Enter* the **[Metacenter]** data, **[GMt] = "1.48",** ***check*** **[Adjust KG at runtime to make SMP GM=GMt]**
  - SMP may not be able to load the full load case and lay have only used the lightship weight distribution, if that is the case manually enter the additional loads (SRS, Personnel and Additional Load) as lumped weights at the closest station to their longitudinal location.
- *Select* **[File]>[Save]**
- Sea State entry for sea states 4 and 5 (Faltinsen 32).
  - *Select* the **[Sea States] tab**
  - *Select* **[Wave Spectrum] = [Bretschneider]**
  - *Enter* **[Sig Wave Heights] = "6.170, 8.200, 10.700" ft**
  - *Enter* **[Modal Wave Period(s)] = "7.000, 8.000, 9.000, 10.000, 11.000"**
  - *Select* the **[Responses] tab**
  - *Select* **[Statistic for Roll Iteration and Response Output] = "Highest in 50".** Since the LARS frame is expected to be transitioning from the deployed PRM deployed position to the stowed position in less than five minutes, this statistic will capture the max responses for the given wave periods for a time greater than five minutes (John J. McMullen Associates, 3, 4).
- Enter the Motion point to solve for the response at the head of the LARS A-Frame.
  - *Select* the **[Motions Pts] tab**
  - *Click* **[Add]**
  - *Enter* the motion point data: **[Name] = "Hd A-fm ROV over water", [Station (ft-MS)] = - (location of AP from MS +17.46 ft), [Waterline (ft-BL)] = depth +22.8 ft.** For the T-ATF example the motion point entry is as shown in Figure A.20.

Motion Points

#	Name	Station [ft-MS]	Half Breadth [ft-CL]	Waterline [ft-BL]	Disp	Vel	Accel	Body Accel	MSI	Slide	Tip
1	Hd A-fm ROV over Water	114.960	0.000	47.800	☑	☑	☑	☐	☐	☐	☐

Figure A.20. Motion at a Point Entry

- Validate the input data
  - *Select* **[Tools]>[Check and Repair SMP Model]**
  - *Click* **[OK]**
  - The input data card can also be reviewed by *selecting* the **[INP/IRG]** tab
    - *Select* **[File]>[Save]**

2.5.2. SMP Simulation and Postprocessing

- To run SMP, *select* **[Tools]>[Run SMP and PostProcess ...]**
- *Click* **[OK]** for any dialog boxes
- The SMP modules will run and, upon completion, start the SMP Post Processor

2.5.3. Analysis of Results

- Change the Units, if necessary:
  - *Select* **[Tools]>[Options],** *select* the **[Units and Precision] tab,** *click* the **[ft-LT] button.** *Click* **[OK]**
- Establish adequacy for Sea State 4:
  - *Select* the **[Responses Tab],** *select* **[Sig Wave Ht]= "8.199" ft** and **[Modal Period] = "9.00"**
  - To check for the Vertical Acceleration adequacy of the motion point (should be less than 0.31 g), *scroll and select* **[Type] = "Vert Accel", [Location] = "Hd A-fm ROV over water".** To arrange the max response accelerations in order of magnitude (to find the max), *click twice* the **[Value Single Amp]** header. The view pane should appear as shown in Figure A.21. Since this max response (0.427 g) exceeds the requirement, this example ship would not be adequate as a VOO. Also examine the modal periods surrounding the most likely period (8 and 10 sec for 9sec).

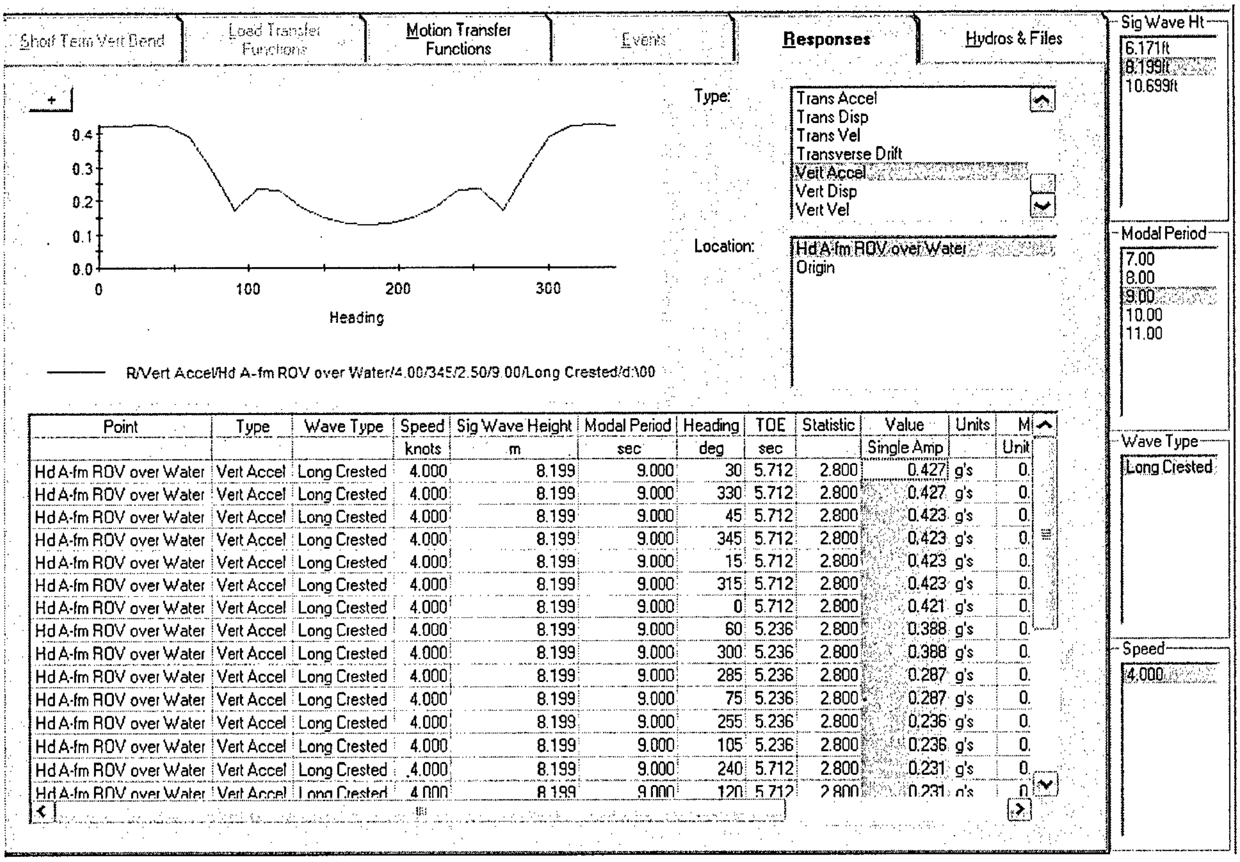


Figure A.21. SMP Postprocessor Response Output

- o Repeat this examination procedure for longitudinal acceleration, transverse acceleration and compare to the table of adequacy values (Table A.8)
- o Repeat this procedure for any other sea states of interest.

Table A.8. Criteria for Seakeeping

Parameter	**Value**
SEAKEEPING, up to Sea State 4, accelerations at head of LARS A-Frame at max aft outreach. (John J. McMullen Associates, 7, 8)	
Longitudinal Acceleration (max)	0.20 g
Transverse Acceleration (max)	0.39 g
Vertical Acceleration (max)	0.31 g

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APPENDIX B. COMPARISON ANALYSIS RESULTS

FULL STABILITY ANALYSIS RESULTS

VOO Selection Process Comparison					
STARTING INFO					
Characteristic	units	Actual TATF	VOO TATF	% Diff	
LOA	ft	226	226	0.00%	
B	ft	42	42	0.00%	
DWT	LT	814	814	0.00%	
T	ft	15.5	15.5	0.00%	full load
D	ft	20	20	0.00%	
Hull Generation Info					
LBP	ft	195	192.1	-1.49%	estimated as 0.85*LOA
B	ft	42	42	0.00%	
T	ft	15.5	15.5	0.00%	
D0	ft	37	34	-8.11%	actual depths estimated from figure
D3	ft	35	33	-5.71%	
D10	ft	28.5	30	5.26%	
D20	ft	20	20	0.00%	
CP		0.716	0.729	1.82%	
CX		0.893	0.906	1.46%	
Main Dk ht	ft	28.5	30	5.26%	same as D10
Loading Conditions					
Lightship					
Weight	LT	1555.7	1,547	-0.56%	iterated to get T=15.5
LCG	ft AFP	91.82	93.83	2.19%	
VCG	ft ABL	19.34	19.5	0.83%	
Departure LARS vert					
Displacement	LT	2096.43	2277	8.61%	
LCG	ft AFP	102.93	99.59	-3.24%	
VCG	ft ABL	18.18	17.51	-3.69%	
SRS	LT	160.56	160.56	0.00%	
SRS LCG	ft AFP	167.66	167.66	0.00%	
SRS VCG	ft ABL	28.54	28.54	0.00%	
DISSB Crew	LT	0.00	0	0.00%	
DISSB Crew LCG	ft AFP	0.00	0	0.00%	
DISSB Crew VCG	ft ABL	0.00	0	0.00%	

Addl (incl tanks)	LT	379.89	570	50.04%	0.7 * DWT
Addl LCG	ft AFP	121.05	96.05	-20.65%	MS
Addl VCG	ft ABL	8.84	8	-9.46%	0.45 * D
Max VCG	ft ABL	18.24	17.49	-4.11%	KMt(17.98)-ReqGM(.49) ***Used IMO (since POSSE USCG doesn't have req'd GM, Max VCG=KMt-GM(Reqd)
Actual VCG incl FSC	ft ABL	18.18	17.51	-3.69%	
VCG Margin	ft	0.06	-0.02	-133.33%	
Mid-Voyage LARS vert					
Displacement	LT	2062.94	2120	2.77%	
LCG	ft AFP	102.58	100.02	-2.50%	
VCG	ft ABL	18.15	17.99	-0.88%	
SRS	LT	160.56	160.56	0.00%	
SRS LCG	ft AFP	167.66	167.66	0.00%	
SRS VCG	ft ABL	28.54	28.54	0.00%	
DISSB Crew	LT	5.16	5.16	0.00%	
DISSB Crew LCG	ft AFP	162.83	162.83	0.00%	
DISSB Crew VCG	ft ABL	25.49	25.49	0.00%	
Addl (incl tanks)	LT	341.40	407.00	19.21%	0.5 * DWT
Addl LCG	ft AFP	117.99	96.05	-18.59%	MS
Addl VCG	ft ABL	7.57	8.00	5.62%	0.4 * D
Max VCG	ft ABL	18.42	17.63	-4.29%	KMt(18.12)-ReqGM(.49)
Actual VCG incl FSC	ft ABL	18.15	17.99	-0.88%	
VCG Margin	ft	0.27	-0.36	-233.33%	
Return LARS vert					
Displacement	LT	2026.26	2038	0.58%	
LCG	ft AFP	101.33	100.17	-1.14%	
VCG	ft ABL	18.35	18.07	-1.53%	
SRS	LT	160.56	160.56	0.00%	
SRS LCG	ft AFP	167.66	167.66	0.00%	
SRS VCG	ft ABL	28.54	28.54	0.00%	
DISSB Crew	LT	5.16	5.16	0.00%	
DISSB Crew LCG	ft AFP	162.83	162.83	0.00%	
DISSB Crew VCG	ft ABL	25.49	25.49	0.00%	
Addl (incl tanks)	LT	304.83	326.00	6.94%	0.3 * DWT
Addl LCG	ft AFP	113.90	96.05	-15.67%	MS
Addl VCG	ft ABL	7.13	6.00	-15.90%	0.3 * D
Max VCG	ft ABL	18.54	17.74	-4.31%	KMt(18.12)-ReqGM(.49)
Actual VCG incl FSC	ft ABL	18.35	18.07	-1.53%	
VCG Margin	ft	0.19	-0.33	-273.68%	

FULL SEAKEEPING RESULTS

Ship Motion Comparison at SS4						
Model:	Units	JJMA	DTCEL	VOO	%DJ	%DD
T	ft	14.96	14.05	14.97	0.07%	6.55%
Disp	LT	2240	2035	2277	1.65%	11.89%
LCG	ft AFP	101.37	102.35	99.59	-1.76%	-2.70%
VCG	ft ABL	17.1	18.12	17.51	2.40%	-3.37%
Ship Motion						
Sig Wave Ht	ft	8.2	8.2	8.199	-0.01%	-0.01%
Wave Pk Per	s	9	9	9	0.00%	0.00%
Max Roll	deg	13.6	10.53	1.998	-85.31%	-81.03%
Resp Per	s	10	9.601	8.727	-12.73%	-9.10%
Max Roll Vel	deg/s	9.2	5.985	6.007	-34.71%	0.37%
Resp Per	s	10	9.191	7.48	-25.20%	-18.62%
Max Roll Accel	deg/s^2	6.6	4.195	1.981	-69.98%	-52.78%
Resp Per	s	10	7.513	5.712	-42.88%	-23.97%
Max Pitch	deg	6	5.29	3.559	-40.68%	-32.72%
Resp Per	s	8	7.545	6.981	-12.74%	-7.48%
Max Pitch Vel	deg/s	5.19	4.785	11.656	124.59%	143.59%
Resp Per	s	7	6.251	6.411	-8.41%	2.56%
Max Pitch Accel	deg/s^2	4.79	5.098	4.107	-14.26%	-19.44%
Resp Per	s	7	5.128	5.712	-18.40%	11.39%
"LLA Pivot Axis Motion"						
Max Long Disp	ft	3.15	2.606	2.502	-20.57%	-3.99%
Resp Per	s	7	9.082	11.22	60.29%	23.54%
Max Long Vel	ft/s	2.9	1.803	1.458	-49.72%	-19.13%
Resp Per	s	7	7.862	11.023	57.47%	40.21%
Max Long Accel	ft/s^2	0.092	0.045	0.042	-54.35%	-6.67%
Resp Per	s	6	6.509	3.307	-44.88%	-49.19%
Max Trans Disp	ft	6.85	9.111	8.163	19.17%	-10.41%
Resp Per	s	9	7.706	8.727	-3.03%	13.25%

Max Trans Vel	ft/s	5.48	7.429	7.314	33.47%	-1.55%
Resp Per	s	9	6.865	6.411	-28.77%	-6.61%
Max Trans Accel	ft/s^2	0.151	0.215	0.286	89.40%	33.02%
Resp Per	s	8	5.817	5.236	-34.55%	-9.99%
Max Vert Disp	ft	12.9	11.818	8.212	-36.34%	-30.51%
Resp Per	s	8	6.994	7.306	-8.68%	4.46%
Max Vert Vel	ft/s	10.8	10.618	8.26	-23.52%	-22.21%
Resp Per	s	8	6.339	5.71	-28.63%	-9.92%
Max Vert Accel	ft/s^2	0.31	0.346	0.298	-3.87%	-13.87%
Resp Per	s	7	5.221	5.236	-25.20%	0.29%

APPENDIX C. SENSITIVITY ANALYSIS RESULTS

INPUTS:

SRDRS Sensitivity Analysis					
				PNA	
Input Variables			low	typical	high
Cb			0.5	0.66	0.8
Cx (Cm)			0.8	0.906	0.99
VCG/D10			0.4	0.65	0.9
LCG/L			0.05	-0.003	-0.05
Cp			0.6	0.729	0.8
Stability Output		Seakeeping Output			
GM		Roll, a			
Area to 30deg		Pitch, a			
Max GZ		Heave, a			
gm					
Asset Data:					
Beam	42	ft			
LBP	195	ft			
Draft	14.95	ft			
D0	20				
D3	20				
D10	20				
D20	20				

JMP DESIGN SPACE RUN PATTERN

Input Variables	T-ATF Values		low	typical	high
Cp			0.6	0.729	0.8
Cx (Cm)			0.83	0.906	0.98
VCG/D10			0.8	0.84	0.96
LCG/L			0.55	0.5	0.45
Run Pattern					
Run #	Pattern	X1	X2	X3	X4
1	0A00	0	1	0	0
2	+-++	1	-1	1	1
3	00A0	0	0	1	0
4	--++	-1	-1	1	1
5	++++	1	1	1	1
6	++-+	1	1	-1	1
7	+-+-	1	-1	1	-1
8	-+++	-1	1	1	1
9	000a	0	0	0	-1
10	00a0	0	0	-1	0
11	----	-1	-1	-1	-1
12	+---	1	-1	-1	-1
13	A000	1	0	0	0
14	0000	0	0	0	0
15	-++-	-1	1	1	-1
16	a000	-1	0	0	0
17	--+-	-1	-1	1	-1
18	0a00	0	-1	0	0
19	---+	-1	-1	-1	1
20	-+--	-1	1	-1	-1
21	000A	0	0	0	1
22	++--	1	1	-1	-1
23	-+-+	-1	1	-1	1
24	+--+	1	-1	-1	1
25	+++-	1	1	1	-1

Run Pattern translated into values:

						Actual	Actual
	Cp	Cx (Cm)	VCG/D10	LCG/L		VCG (ft)	LCG (ft-MS)
1	0.729	0.98	0.84	0.5		16.8	0
2	0.8	0.83	0.96	0.45		19.2	9.75
3	0.729	0.906	0.96	0.5		19.2	0
4	0.6	0.83	0.96	0.45		19.2	9.75
5	0.8	0.98	0.96	0.45		19.2	9.75
6	0.8	0.98	0.8	0.45		16	9.75
7	0.8	0.83	0.96	0.55		19.2	-9.75
8	0.6	0.98	0.96	0.45		19.2	9.75
9	0.729	0.906	0.84	0.55		16.8	-9.75
10	0.729	0.906	0.8	0.5		16	0
11	0.6	0.83	0.8	0.55		16	-9.75
12	0.8	0.83	0.8	0.55		16	-9.75
13	0.8	0.906	0.84	0.5		16.8	0
14	0.729	0.906	0.84	0.5		16.8	0
15	0.6	0.98	0.96	0.55		19.2	-9.75
16	0.6	0.906	0.84	0.5		16.8	0
17	0.6	0.83	0.96	0.55		19.2	-9.75
18	0.729	0.83	0.84	0.5		16.8	0
19	0.6	0.83	0.8	0.45		16	9.75
20	0.6	0.98	0.8	0.55		16	-9.75
21	0.729	0.906	0.84	0.45		16.8	9.75
22	0.8	0.98	0.8	0.55		16	-9.75
23	0.6	0.98	0.8	0.45		16	9.75
24	0.8	0.83	0.8	0.45		16	9.75
25	0.8	0.98	0.96	0.55		19.2	-9.75

Stability Analysis Results

	Area to 40deg	Max GZ	Init GMt	MT1"	
	ft-deg	ft	ft	ft-LT/in	
1	20.44	1.04	0.73	190	
2	20.77	0.81	1.59	216	
3	13.12	0.55	0.72	182	
4	7.02	0.34	1.16	167	
5	7.44	0.51	-0.46	211	
6	34.36	1.76	1.59	211	
7	20.77	0.81	1.59	216	
8	5.3	0.26	0.51	174	
9	33.79	1.33	2.26	182	
10	40.68	1.62	2.78	182	
11	33.69	1.16	3.22	167	
12	48.34	1.9	3.65	216	
13	40	1.64	2.53	208	
14	33.79	1.33	2.26	182	
15	5.3	0.26	0.51	174	
16	25.21	0.87	2.5	157	
17	7.02	0.34	1.16	167	
18	35.68	1.34	2.72	188	
19	33.69	1.16	3.22	167	
20	32.62	1.22	2.57	174	
21	33.79	1.33	2.26	182	
22	34.36	1.76	1.59	211	
23	32.62	1.22	2.57	174	
24	48.34	1.9	3.65	216	
25	7.44	0.51	-0.46	211	

Seakeeping Analysis Results, Motion at the head of LARS with PRM over water:

		Max Vert Accel	
	g	hdg	dev
1	0.381	0	0.00224
2	0.326	30	0.05724
3	0.382	0	0.00124
4	0.383	0	0.00024
5	0.364	0	0.01924
6	0.364	0	0.01924
7	0.390	0	0.00676
8	0.400	0	0.01676
9	0.482	0	0.09876
10	0.383	0	0.00024
11	0.384	0	0.00076
12	0.388	15	0.00476
13	0.346	0	0.03724
14	0.363	0	0.02024
15	0.395	0	0.01176
16	0.422	0	0.03876
17	0.383	0	0.00024
18	0.370	30	0.01324
19	0.383	0	0.00024
20	0.482	0	0.09876
21	0.364	0	0.01924
22	0.360	15	0.02324
23	0.400	0	0.01676
24	0.326	30	0.05724
25	0.360	15	0.02324

	Max Trans Accel		
	g	hdg	dev
1	0.390	60	-0.099
2	0.319	75	-0.170
3	0.382	60	-0.107
4	0.372	60	-0.117
5	0.361	60	-0.128
6	0.361	60	-0.128
7	0.398	60	-0.091
8	0.324	60	-0.165
9	0.531	120	0.042
10	0.612	60	0.123
11	0.723	60	0.234
12	0.518	105	0.029
13	0.750	60	0.261
14	0.335	75	-0.154
15	0.345	60	-0.144
16	0.687	60	0.198
17	0.319	75	-0.170
18	0.593	60	0.104
19	0.518	60	0.029
20	0.599	60	0.110
21	0.347	120	-0.142
22	0.434	60	-0.055
23	0.379	60	-0.110
24	1.195	105	0.706
25	0.430	75	-0.059

APPENDIX D. AHT AND BARGE EXAMPLE ANALYSIS

STARTING INFO		2507			
Characteristic	units	Neftegaz-51	units	Converted	LARS location (ft MS)
LOA	m	81.37	ft	266.962	150.941
B	m	16.3	ft	53.47769	
DWT	mt	1350	LT	1328.679	
T	m	4.91	ft	16.10892	
D	m	7.2	ft	23.62205	46.42205
Deck Length	m	38.75	ft	127.1326	
Deck Width	m	11.35	ft	37.23753	
Deck Strength	t/m^2	5	LT/ft^2	0.471965	
Deck Cargo	mt	700	LT	688.9449	
Hull Generation Info					
LBP	ft	256.00		adjusted to get ASSET LOA to match	
B	ft	53.48			
T	ft	16.11			
D0	ft	40.16			
D3	ft	36.61			
D10	ft	35.43			
D20	ft	23.62			
CP		0.72			
CX		0.89			
Main Dk ht	ft	23.62			
Loading Conditions					
Lightship					
Weight	LT	2690			
LCG	ft AFP	130.1			
VCG	ft ABL	23.0314968			
Departure LARS vert					
Displacement	LT	3803.00			
LCG	ft AFP	133.66			
VCG	ft ABL	20.44			
SRS	LT	183.00			
SRS LCG	ft AFP	214.76	ft MS	-86.76	
SRS VCG	ft ABL	32.31			
DISSB Crew	LT	0.00			
DISSB Crew LCG	ft AFP	0.00	ft MS	128	
DISSB Crew VCG	ft ABL	0.00			
Addl (incl tanks)	LT	930.08			0.7 * DWT
Addl LCG	ft AFP	128.00	ft MS	0	MS
Addl VCG	ft ABL	10.63			0.45 * D

Area to 40 deg	ft-deg	66.74			
Max GZ	ft	3.38			
Initial GM	ft	3.80			
Mid-Voyage LARS vert					
Displacement	LT	3543.00			
LCG	ft AFP	122.16			
VCG	ft ABL	20.97			
SRS	LT	183.00			
SRS LCG	ft AFP	214.76	ft MS	-86.76	
SRS VCG	ft ABL	32.31			
DISSB Crew	LT	5.16			
DISSB Crew LCG	ft AFP	162.83	ft MS	-34.83	
DISSB Crew VCG	ft ABL	25.49			
Addl (incl tanks)	LT	664.34			0.5 * DWT
Addl LCG	ft AFP	128.00	ft MS	0	MS
Addl VCG	ft ABL	9.45			0.4 * D
Area to 40 deg	ft-deg	63.46			
Max GZ	ft	3.14			
Initial GM	ft	3.88			
.					
Return LARS vert					
Displacement	LT	3277.00			
LCG	ft AFP	121.69	ft MS	6.31	
VCG	ft ABL	21.61			
SRS	LT	183.00			
SRS LCG	ft AFP	214.76	ft MS	-86.76	
SRS VCG	ft ABL	32.31			
DISSB Crew	LT	5.16			
DISSB Crew LCG	ft AFP	162.83	ft MS	-34.83	
DISSB Crew VCG	ft ABL	25.49			
Addl (incl tanks)	LT	398.60			0.3 * DWT
Addl LCG	ft AFP	128.00	ft MS	0	MS
Addl VCG	ft ABL	7.09			0.3 * D
Area to 40 deg	ft-deg	59.54			
Max GZ	ft	2.79			
Initial GM	ft	3.86			
LARS Long Accel	g	0.052			
LARS Trans Accel	g	0.313			
LARS Vert Accel	g	0.264			

STARTING INFO		Ocean Going Barge (McDonough Marine Service			
Characteristic	units	200x50x13	units		lars location
LOA	ft	200			117.46
B	ft	50			

DWT	LT	1460	for 6ft of freeboard		
T	ft	7			
D	ft	13			35.8
Deck Length	ft	200			
Deck Width	ft	50			
Deck Strength	LT/ft^2				
Deck Cargo	LT	2600			
Hull Generation Info					
LBP	ft	200.00			
B	ft	50.00			
T	ft	7.00			
D0	ft	13.00			
D3	ft	13.00			
D10	ft	13.00			
D20	ft	13.00			
CP		1.00			
CX		1.00			
Main Dk ht	ft	13.00			
Loading Conditions					
Lightship					
Weight	LT	545			
LCG	ft AFP	100			
VCG	ft ABL	6.5			
Departure LARS vert					
Displacement	LT	1128.00			
LCG	ft AFP	99.87			
VCG	ft ABL	8.43			
SRS	LT	183.00			
SRS LCG	ft AFP	158.76	ft MS	-58.76	
SRS VCG	ft ABL	21.69			
DISSB Crew	LT	0.00			
DISSB Crew LCG	ft AFP	0.00	ft MS	100	
DISSB Crew VCG	ft ABL	0.00			
Addl (incl tanks)	LT	400.00			Ballast for stability
Addl LCG	ft AFP	27.00	ft MS	73	
Addl VCG	ft ABL	5.00			
Area to 40 deg	ft-deg	380.34			
Max GZ	ft	12.19			
Initial GM	ft	46.61			
Mid-Voyage LARS vert					
Displacement	LT	1133.00			
LCG	ft AFP	100.95			
VCG	ft ABL	8.48			

SRS	LT	183.00			
SRS LCG	ft AFP	158.76	ft MS	-58.76	
SRS VCG	ft ABL	21.69			
DISSB Crew	LT	5.16			
DISSB Crew LCG	ft AFP	162.83	ft MS	-62.83	
DISSB Crew VCG	ft ABL	18.49			
Addl (incl tanks)	LT	400.00			
Addl LCG	ft AFP	100.00	ft MS		
Addl VCG	ft ABL	5.20			
Area to 40 deg	ft-deg	378.86			
Max GZ	ft	12.15			
Initial GM	ft	46.31			
Return LARS vert					
Displacement	LT				
LCG	ft AFP				
VCG	ft ABL				
SRS	LT				
SRS LCG	ft AFP				
SRS VCG	ft ABL				
DISSB Crew	LT				
DISSB Crew LCG	ft AFP				
DISSB Crew VCG	ft ABL				
Addl (incl tanks)	LT				
Addl LCG	ft AFP				
Addl VCG	ft ABL				
Area to 40 deg	ft-deg				
Max GZ	ft				
Initial GM	ft				
LARS Long Accel	g	0.046			
LARS Trans Accel	g	0.498			
LARS Vert Accel	g	0.217			